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TECHNICAL REPORT SL-84-13

BLAST DOOR AND ENTRYWAY DESIGN AND EVALUATION

by

David W. Hyde, Sam A. Kiger

Structures Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
PO Box 631
Vicksburg, Mississippi 39180

July 1984
Final Report

Approved For Public Release. Distribution Unlimited

Prepared for Federal Emergency Management Agency
Washington, DC 20472

Under Interagency Agreement No. EMW-E-1118

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Objectives of this project were to design and test a walk-in, reinforced concrete blast shelter entryway and blast door. Two door configurations were designed, constructed, and tested: a commercially available standard exterior door with special supports, and a 3-inch-thick reinforced concrete door. The entryway and closures were tested at the DIRECT COURSE event at White Sands Missile Range, New Mexico. The DIRECT COURSE event was a high-explosive test

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20. ABSTRACT (Continued).

sponsored by the Defense Nuclear Agency in October 1983. A 1-KT simulated nuclear airblast and ground motion environment were provided by detonation of 609 tons of an ammonium nitrate-fuel oil (ANFO) mixture at a height of burst of 166 feet. The peak recorded pressure at the opening to the entryway was 69 psi and peak reflected pressure at the center of the blast door was 159 psi.

The reinforced concrete door survived the airblast effects of DIRECT COURSE with only slight permanent deformation. The door could be easily opened and closed again. The commercial door was totally destroyed during the test. Posttest analyses indicate that the reinforced concrete blast door will successfully withstand the airblast effects of a 1-MT nuclear detonation at the 50-psi overpressure range.

PREFACE

This investigation, sponsored by the Federal Emergency Management Agency, under Interagency Agreement No. EMW-E-1118, was conducted by personnel of the Structures Laboratory (SL), U. S. Army Engineer Waterways Experiment Station (WES) during the period January 1983 through December 1983.

This study was performed under the general supervision of Messrs. Bryant Mather, Chief, SL, and J. T. Ballard, Assistant Chief, SL, and under the direct supervision of Dr. Jimmy P. Balsara, Acting Chief, Structural Mechanics Division (SMD), SL. This report was prepared by CPT D. W. Hyde, CE, and Dr. S. A. Kiger of the Research Group, SMD.

Commander and Director of WES during the conduct of the study and the preparation of this report was COL Tilford C. Creel, CE. Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
inches	0.0254	metres
megatons (nuclear equivalent of TNT)	0.004184	terajoules
kilotons (nuclear equivalent of TNT)	4.184	terajoules
pounds (force) per square inch (psi)	0.006895	megapascals
pounds (mass)	0.45359237	kilograms
pounds per cubic foot	0.1601846	grams per cubic centimetre
psi per inch	0.271447	megapascals per metre
tons (nuclear equivalent of TNT)	4184.0	megajoules

BLAST DOOR AND ENTRYWAY DESIGN AND EVALUATION

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

In the event of an imminent nuclear strike, current Civil Defense planning calls for the evacuation of nonessential personnel to safe host areas, and the construction of blast shelters to protect the key workers remaining behind. These shelters will be designed to resist blast, radiation, and associated effects at the 50-psi* overpressure level for a 1-MT weapon. One of the key elements to the survivability of these shelters is the vulnerability of the shelter closure and entryway.

Several blast shelter entryways, some including blast doors, were tested in the aboveground atomic tests at the Nevada Test Site during the 1950's.[1-7] The blast doors or closures tested were either massive reinforced concrete doors,[4,5] vertical shaft entryways with a submarine-type hatch,[1,2,3] steel doors with beam stiffeners,[6] or doors tested at less than 10 psi.[7] More recent tests have reexamined the steel door[8] and the vertical shaft with a hatch at ground level.[9]

The most cost-efficient closure and entryway system, one whose survivability has clearly been demonstrated, is the vertical shaft with a hatch-type closure. However, if a vertical entryway is used for a large shelter (100-person capacity or larger) it may not be possible to get everyone into the shelter in the allotted time (normally 15 minutes). Also, if the shelter is to be a dual-use facility, the vertical entrance is not acceptable. Therefore, a cost-efficient, walk-down entryway and blast door design is needed for large-capacity shelters such as the deliberate 100-person-capacity key worker blast shelter that is currently being designed for the Federal Emergency Management Agency.

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*A table of factors for converting non-SI to SI (metric) units of measurement is presented on page 4.

1.2 OBJECTIVES AND SCOPE

The objectives of this project were to design a walk-in, reinforced concrete entryway and blast door and evaluate the design in a 1-KT simulated airblast environment in the DIRECT COURSE event at White Sands Missile Range (WSMR), N. Mex. The DIRECT COURSE event is described in Section 3.2. Various blast door configurations were considered and from those analyzed, a prototype door was selected for use in the entryway. A commercially available fire-resistant door with special supports was also tested. By using 1/10-scale models, airblast loading data for a 1-MT weapon were obtained for both a single-tunnel dead-end entryway system and a double-tunnel pass-through entryway system. These data will be used for the analysis of entryways and blast doors for the key worker blast shelter.

1.3 PROCEDURE

Testing was conducted during October 1983 by personnel of the Structures Laboratory, U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss. The entryway system was tested at the DIRECT COURSE event at WSMR. This event was a high-explosive simulation of a 1-KT height-of-burst nuclear weapon sponsored by the Defense Nuclear Agency (DNA). The entryway was constructed at the predicted 50-psi overpressure range. Fourteen channels of airblast data were collected during the test. All data were recorded on magnetic tape and later reduced to a digital format.

CHAPTER 2

STRUCTURAL DETAILS AND MATERIAL PROPERTIES

2.1 ENTRYWAY

2.1.1 Shape

Pedestrian flow-rate studies have been conducted on the movement of personnel through protective shelter entryways.[10] The dimensions of the prototype entryway were selected to provide access to approximately 100 personnel in about 2 minutes.

The stairwell in the test entryway was 4 feet wide with a 7-foot vertical clearance throughout. The stair risers were 7-3/4 inches high; stair treads were 10 inches deep. The stairway had a 4- × 4-foot landing about 8 feet below the surface. Both doors tested provided a clearance of 3- × 7-feet. The ceiling height immediately in front of each door was 10 feet, which matches the ceiling height inside the proposed key worker blast shelter. This facilitates building a continuous roof slab inside and outside the shelter. Sketches of the entryway are shown in Figures 2.1 and 2.2.

2.1.2 Airblast Prediction

Prior to the design of the doors or structural elements, it was necessary to obtain a pressure-time history prediction at various points inside the entryway. A surface overpressure of 50 psi was predicted by DNA personnel at a slant range of 503 feet, or a horizontal range of approximately 475 feet. The prediction for pressures inside the entryway was based on the open end of the entryway facing ground zero, which provides a worst case loading for the closures. It will be noted from Figure 2.3 that the orientation of the entryway provided a nearly direct line of sight from the end of the entryway to the charge.

Pressures at various points inside the entryway were calculated with the ANSWER computer code, which is based on a modification of the work found in References 11, 12, and 13. The ANSWER code was developed at WES in the Explosion Effects Division of the Structures Laboratory. The pressure-time history computed at the center of the blast door and used for the blast door response analysis is shown in Figure 2.4. From Figure 2.4, the predicted peak pressure on the blast door is about 142 psi.

In examining the configuration of the entryway, it is apparent that with the given orientation of the stairway, the wall and roof slabs will be loaded primarily from the inside. However, it is unlikely that the backfill surrounding the structure would allow enough deflection in the slabs to cause failure. Hence the worst case loading for the wall and roof slabs would be with the open end of the entryway facing away from ground zero, so that the slabs are initially loaded by the soil-transmitted pressures only. Since the survival of personnel inside the protective shelter is more dependent on the vulnerability of the closure itself, the entryway was tested for a worst case loading on the doors, i.e., with the entryway opening facing ground zero. Obviously, in the case of a real-world blast shelter, if the probable burst point of a nuclear weapon can be determined with any degree of accuracy, the shelter should be oriented in such a way that the entryway opening is facing away from ground zero.

2.1.3 Structural Details

The entryway tested was of reinforced concrete slab-type construction throughout. The roof and floor slabs were 6 inches thick, with 1-7/8 inches of concrete cover to the principal steel in each face. Principal steel consisted of No. 4 bars at 12 inches on center in both tension and compression, giving a steel ratio of 0.43 percent. Temperature steel was No. 3 bars at 12 inches on center, and shear reinforcement was provided with No. 3 U-type stirrups at 12 inches on center. Reinforcement details and dimensions are shown in Figure 2.5. The overall length of the test structure was 29 feet 6 inches. The ground floor was approximately 15 feet 6 inches below the surface. Photographs of the entryway under construction are shown in Figures 2.6-2.10.

2.2 CLOSURES

2.2.1 Configurations Examined

Prior to the design of a blast door, tentative design criteria were established. A minimum static ultimate resistance of 150 psi was selected for the door based on the predicted peak pressure at the door opening. In order to minimize the cost of the hinges and to facilitate handling, the weight of the door was limited to a maximum of 1,500 pounds. The level of protection from prompt radiation provided by the door was also taken into consideration.

Three concepts for a reinforced concrete door configuration were considered (Figure 2.11). In each case the clearance provided by the door opening was taken as 3 feet wide by 7 feet high, with the door overhanging this opening by 4 inches on all edges.

The Type 1 door (Figure 2.11) was a conventional reinforced concrete slab with steel channels running the length of the door to provide a bearing surface for the hinges and latch mechanism. The Type 2 door was of a sandwich-type construction, with steel plates of equal thickness on each side of the door, anchored to the concrete with welded shear studs. The Type 3 door included a steel plate on the tension face (inside) of the door with deformed bars across the short span near the compression face. Hooks welded to the steel plate fix the deformed bars in place and anchor the steel plate to the concrete. High-density concrete was examined in each configuration for its radiation attenuation potential.

Each door configuration was examined for its flexural capacity, weight, and radiation attenuation. Door thickness and steel ratios were varied to obtain a "best case" for each door type. Equations for flexural capacity from Reference 14 were used to calculate the maximum resistance of each door. Results of this evaluation are given in Table 2.1. The value labeled "% rad" indicates the percentage of the radiation level outside the door which will be transmitted through the door. Exact figures for radiation levels penetrating the door are not given, because this phenomenon depends not only on weapon size and range, but also on entryway orientation and weapon type. Reference 10 was used for radiation attenuation calculations.

2.2.2 Analysis of Various Configurations

As indicated in Table 2.1, the Type 1 door met neither the flexural capacity requirements nor the weight restrictions. While the flexural capacity could be raised by constructing a thicker door, this would also raise the weight, which is already higher than the imposed limit. The Type 2 doors, by weight, are much stronger than the Type 1 doors because of the much higher steel ratios. However, the Type 2 doors would present a problem for concrete placement since each outside face is covered by a steel plate. Also, since the rebound force on the door is in the range of 25 percent of the primary load, less steel is needed in the compression face than in the tensile face. The Type 3 door, while not as strong as the Type 2 doors, does meet the

tentative flexural capacity requirement, is lighter than Type 2, and does not present the construction problem posed by a Type 2 door. Based on this evaluation, a Type 3 door, 3 inches thick with 11-gage sheet steel in tension and No. 4 bars at 6 inches on center in compression was selected for further examination.

It will be noted from Table 2.1 that in each case the high-density concrete gave limited additional radiation protection while raising the door's weight considerably. For this reason, high-density concrete was not considered for use in the blast door beyond this evaluation.

2.2.3 Type 3 Door Details

The welded hooks in the Type 3 door serve as shear reinforcement and prevent the steel plate from separating from the concrete during loading. Shear calculations were based on the dynamic reactions at the edges of the door opening, obtained from Reference 15, Table 5.4. The shear reinforcement selected consisted of No. 3 bars at 6 inches on center.

The door is designed to overhang the opening by 4 inches on all edges; therefore, hinges must support the weight of the door and only some of the rebound force. The hinges are subjected to very little stress caused by the primary loading of the door. The predicted rebound force was determined by the use of Figure 9-1.4 in Reference 16 with the following input parameters:

T = natural period of door = 5.5 ms

t_d = predicted duration of load = 120 ms

Assuming a ductility of 10, the ratio of rebound force to primary load is approximately 0.15, which yields 21 psi on the door in rebound. It was assumed that the hinges would carry about one-half of the rebound load, the other half being carried by the latch mechanism. The hinges used were typical heavy-duty strap hinges with 1/2-inch-diameter pins and 18-inch-long, 1/4-inch-thick straps. The four hinges used satisfied the rebound requirements of the door and gave a high factor of safety for the weight of the door alone. The hinge straps were bent by the manufacturer to accommodate the 3-1/8-inch offset of the door. The hinges were fastened to the door with 3-3/8-inch-diameter bolts and anchored to the door frame and supports with 3/8-inch-diameter bolts (Figure 2.12).

The door frame was designed to prevent excessive concrete cracking in the door supports, which are required to carry the entire load placed on the door

in addition to their own load. It was also considered desirable for the door frame to provide a smooth surface which the door could close against, so that a good seal between door and frame could be more easily attained. The door frame was fabricated from 4- × 4-inch steel angles with a 7- × 4-inch angle on the hinged side of the door. Shear studs were welded to the inside of the frame every 6 inches to provide anchorage in the door supports. The door frame was anchored in place before the door supports were formed, so that the frame and supports were an integral unit. The frame may be seen in construction photos (Figures 2.6 and 2.7).

As stated previously, the door supports were required to withstand the total load carried by the door plus the load placed directly on them. With 4 inches of door overhang, 4 inches taken by the hinges, and a minimum of 5 inches of clearance to the end wall from the open door, the door supports were required to project at least 13 inches from the end wall. The dynamic reactions around the edges of the door were obtained from Table 5.4, Reference 15. Based on design calculations, a depth of 15 inches was selected for the support on either side of the door, and the support above the door sloped from 15 inches deep immediately behind the door to 30 inches deep at the ceiling. Principal reinforcement ratio throughout the supports was 0.36 percent.

Strips of the 11-gage sheet steel were cut 3 inches wide and welded to the sides of the door's rear plate before concrete placement to aid in forming the door. The hooks, made from No. 3 reinforcement bars, were cut 5-3/4 inches long, bent through a 135-degree arc, then welded to the steel sheet. The 11-gage sheet was fixed on all edges during welding to prevent excessive warping. The No. 4 bars were fastened to the welded hooks with wire, but were not welded to the side sheets. Prior to concrete placement, the hinges were fastened to the door shell as shown in Figure 2.12.

The blast door was constructed at WES and transported to WSMR prior to construction of the entryway. All steel used in the door was ASTM Grade 50. The concrete placed in the door had an average 28-day strength of 4,210 psi. The complete door shell, prior to concrete placement, is shown in Figure 2.13.

The resistance function of the door was considered bilinear with a maximum resistance of 180 psi (Table 2.1) and a stiffness given by:[15]

$$K = \frac{201\ EI_a}{ba^3} = 657\ \text{psi/in}$$

where

b = long unsupported dimension of door = 84 inches

a = short unsupported dimension of door = 36 inches

The elastic deflection is 180 psi/(657 psi/in) = 0.27 inch.

The maximum response was calculated from a single-degree-of-freedom numerical integration.[15] Results of these calculations are shown in Figure 2.14. The maximum predicted response of the door was 0.36 inch at 5 ms after the door is initially loaded. Therefore, some plastic deformation was expected with a ductility of

$$0.36/0.27 = 1.3$$

and a permanent deflection of about 0.10 inch.

After the blast door was installed in the test structure, it became evident that neither the back face of the door nor the door frame was perfectly plane. To insure the door's airtightness, the small gaps at the door/door frame interface were filled with a typical commercially available flexible caulk. None of the gaps around the door exceeded 1/8 inch prior to filling.

2.2.4 Projected Cost

Given detailed construction drawings of the blast door, a private manufacturing firm was asked to provide an estimate of the cost of building such a door. The figures shown include the estimated cost of all door hardware and the steel door frame:

Individual units:	$1,024 each
Lots of 20 or more:	$ 924 each

2.2.5 Commercial Door and Supports

A commercially available fire-resistant door was tested with specially constructed supports with the objective of minimizing the cost of the closure and simplifying construction. The door was constructed of a fire-retardant foam sandwiched between thin steel sheets. For analysis purposes the door was considered to have negligible flexural capacity.

The three wide-flange beams shown in Figure 2.15 were designed to carry the total load placed on the door. The beams rest in steel boxes constructed of 1/4-inch plate and cast into the concrete door supports. In practice, the

beams would not be set in place until the blast shelter was occupied, at which time they would be mounted in the boxes. The beams, W6 × 12's, weighed approximately 44 pounds each.

Although the beams were capable of supporting the predicted load on the door, there was doubt as to whether the door was capable of supporting the load between each span (24 inches). Spreader plates were designed to transfer the load from the door to the beams. Two different concepts for these plates were examined. First, six separate plates would be hung, two from each beam, to completely cover the door surface. This would in effect make the plates a double cantilever, fixed in the center. Second, two continuous plates, each covering one-half of the door surface, would be placed between the door and the beams. However, if the assumption of negligible flexural capacity for the door is correct, a 1-inch-thick plate would be needed for the smaller cantilever plates, or a 7/8-inch-thick plate for the continuous concept. Each 1-inch steel plate would weigh about 110 pounds, making it unmanageable in the confines between door supports. Also, the cost of the plates would eliminate any economic benefit gained by using a commercially available door. The size of steel plate needed to insure elastic response of the door was impractical and costly. Therefore, a smaller, more manageable plate was selected and a high level of damage was predicted. Six cantilevered plates, 3/16 inch thick, weighing about 20 pounds each, were used to reinforce the door. The plates were supported on the wide-flange beams with steel angles (L1 × 1 × 1/4 inch).

Rebound forces acting on the door were anticipated to be about 25 percent of the primary load, assuming the door survived. To prevent the door from opening during rebound, it was necessary to anchor it to the support beams. L-shaped anchor bolts served this purpose with the small leg of the "L" hooked to the back sides of the support beams. Three 3/8-inch bolts were used at each beam. Photographs of the commercial door and its supports are shown in Figures 2.16 and 2.17.

Approximate cost of the commercial door and its supports is given below:

Materials	Approximate Cost
Steel fire door, fire rating B	$200
Door frame	67

(Continued)

Materials	Approximate Cost
Hinges	17
W6 v 12 beam, 11 feet	108
3/16-inch steel plate & angles	120
1/4-inch plate	45
Total Materials	$557
Labor (Fabrication only; does not include installation costs)	$200
Total Cost	$757

2.3 MODELS

The prototype entryway and closures were to be subjected to a 1-KT simulated 50-psi airblast environment. Test results were intended to verify the vulnerability of the entryway system to this environment. However, 1-MT loading data were required to determine whether the design of the entryway and blast door would be appropriate for future use in protective shelters. One-tenth-scale models were fabricated to obtain loading data, which could then be scaled, using cube-root scaling, to a 1-MT event and used for design calculations of a full-scale entryway.

Two nonresponding models, one single entrance similar to the full-scale structure and one pass-through tunnel, were constructed. The models were fabricated from 1/4-inch steel plate with all joints welded for strength and airtightness. Each model was instrumented with airblast gages and tested with the entrances facing ground zero. A photograph of the 1/10-scale models is shown in Figure 2.18.

Table 2.1. Blast door analysis results.

Slab Thickness	Type 1			Type 2 (1/4-in plate)			Type 2 (11 gage)			Type 3 (11 gage)		
in	WT lb	R psi	% rad	WT lb	R psi	% rad	WT lb	R psi	% rad	WT lb	R psi	% rad
				Standard Concrete, 150 lb/ft^3								
6	2300	110	0.15									
5	1910	70	0.21									
3				1630	532	0.27	1330	244	0.42	1210	180	0.50
2				1280	369	0.48	980	166	0.74			
				High-Density Concrete, 200 lb/ft^3								
6	2975	110	0.06									
5	2470	70	0.09									
3				1980	532	0.18	1680	244	0.24	1560	180	0.32
2				1510	369	0.35	1210	166	0.50			

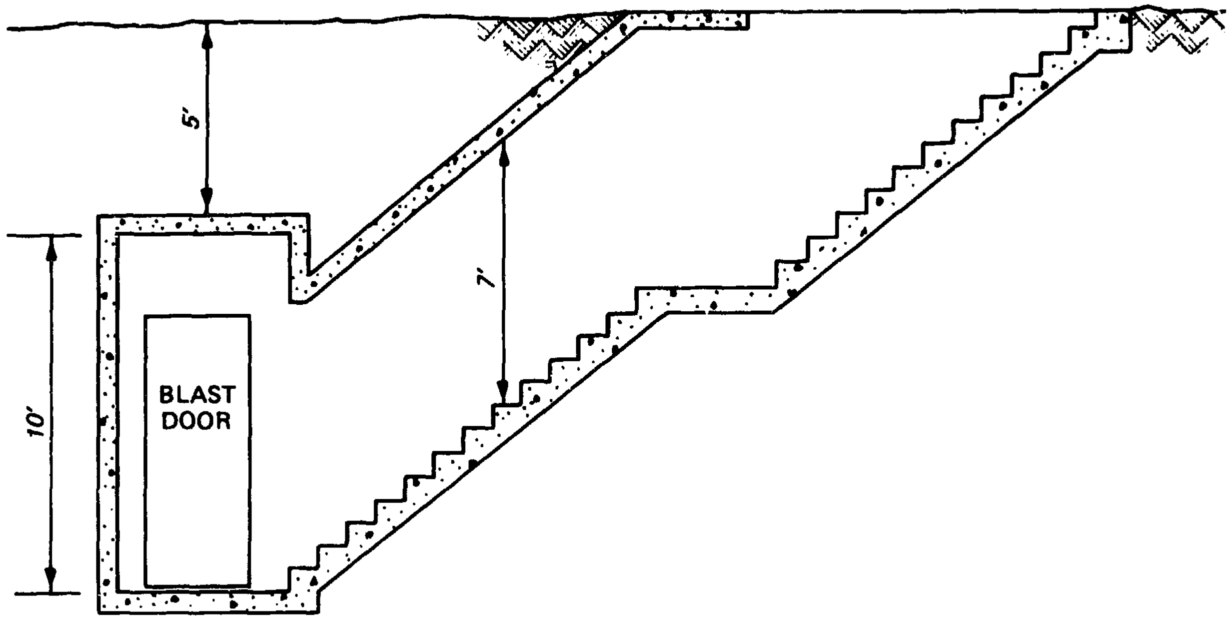

Figure 2.1. Elevation view of entryway.

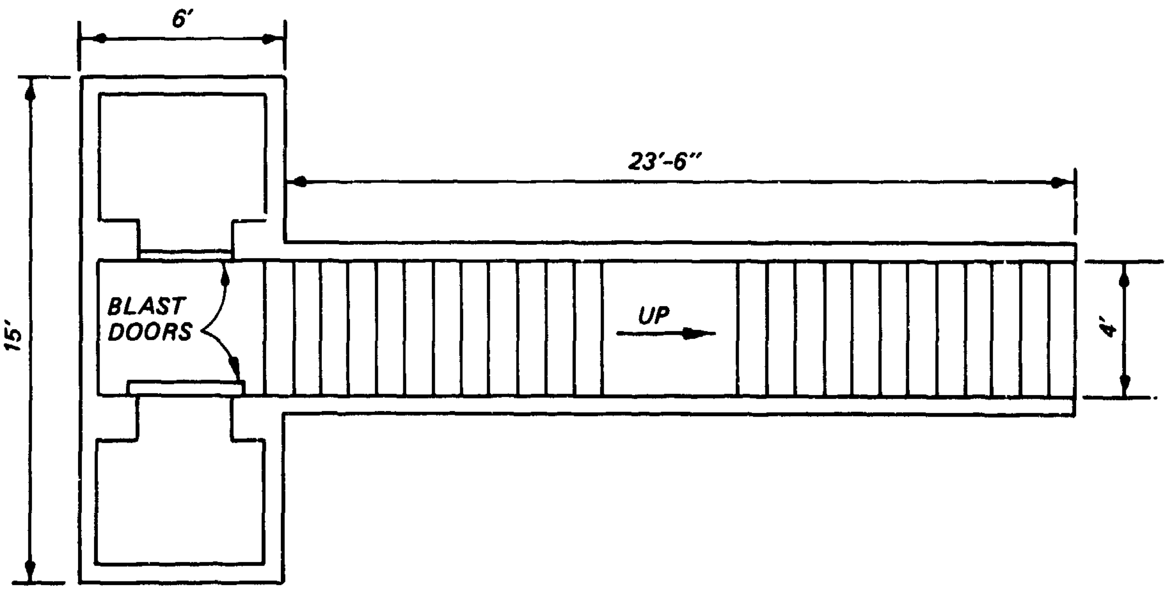

Figure 2.2. Plan view of entryway.

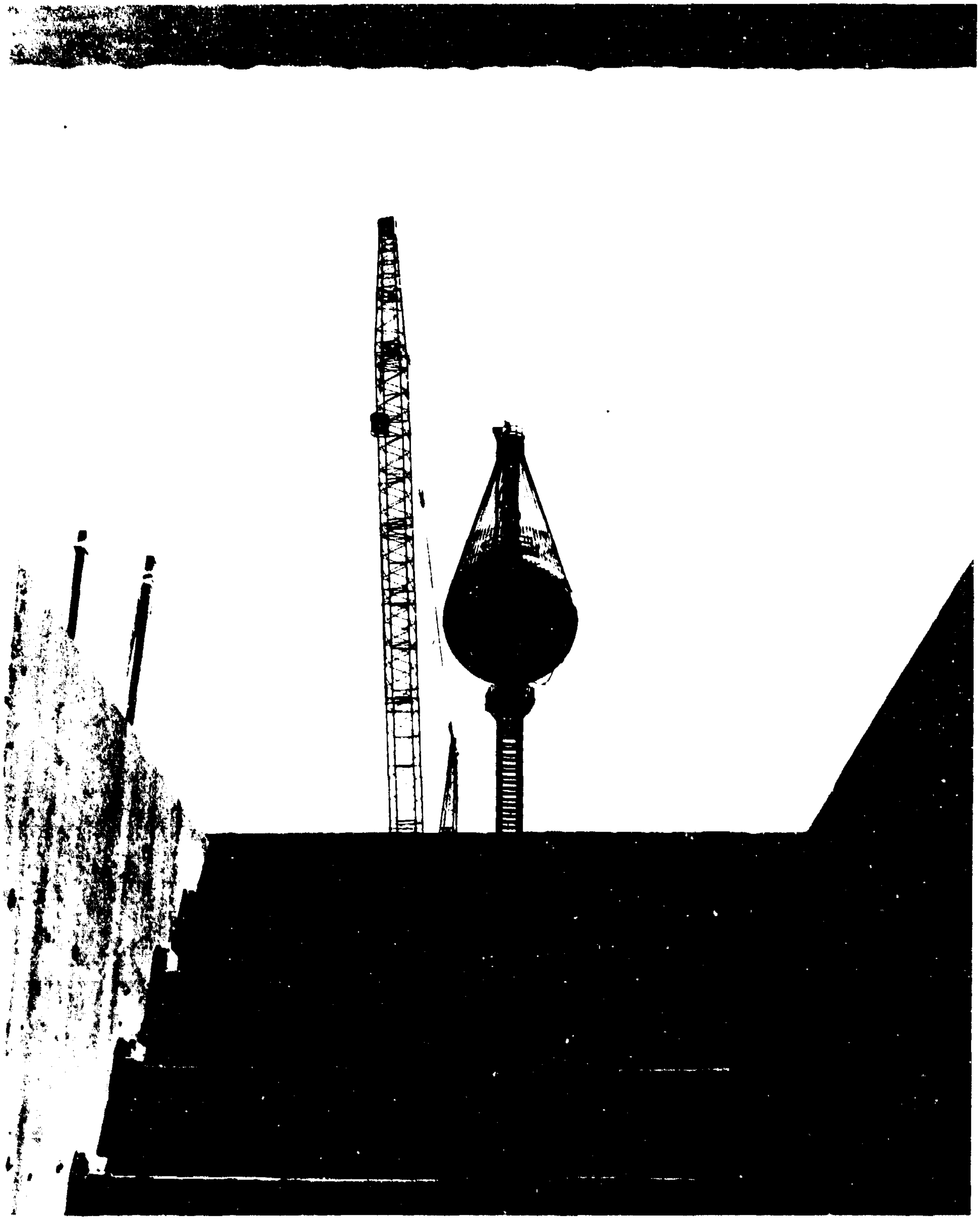

Figure 2.3. Charge tower as seen from entryway interior.

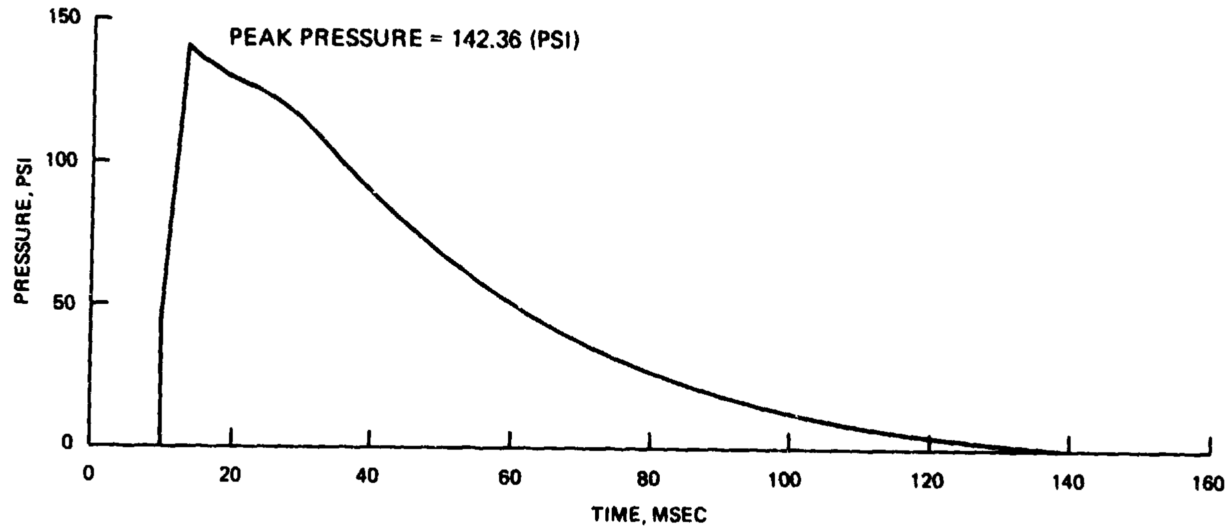

Figure 2.4. Pretest predicted loading history for blast door.

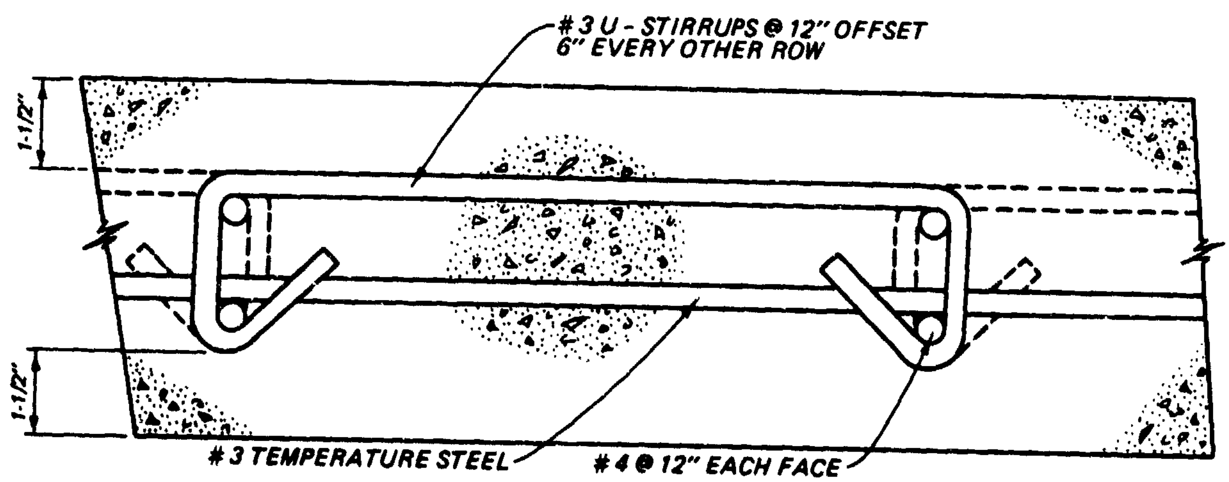

Figure 2.5. Typical slab reinforcement details.

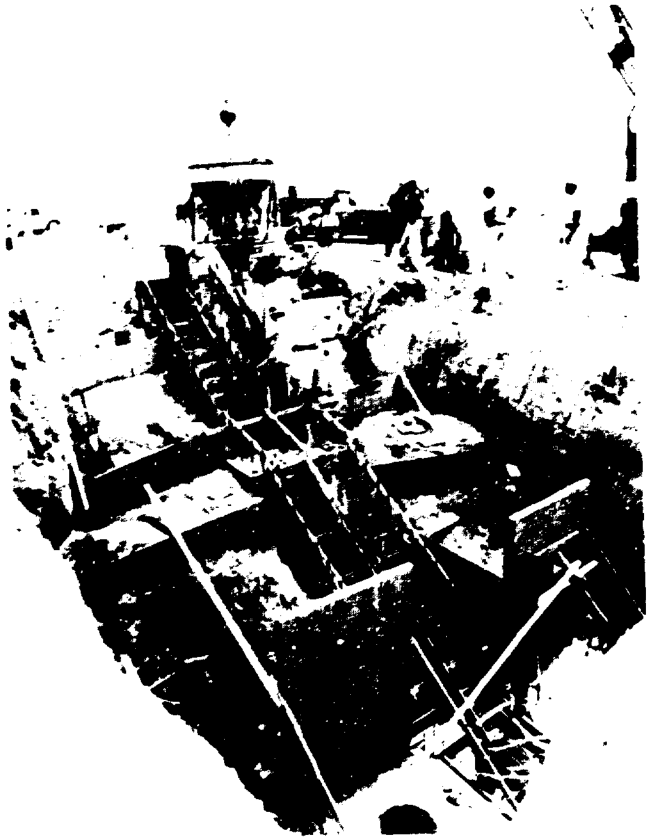

Figure 2.6. Concrete placement in stairs. (Blast door frame at bottom right of photograph.)

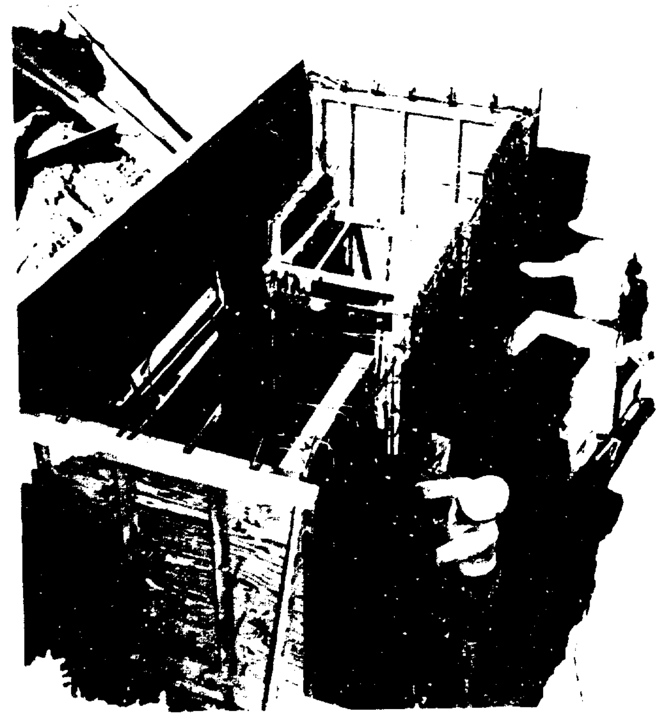

Figure 2.7. Tying reinforcement in end wall.

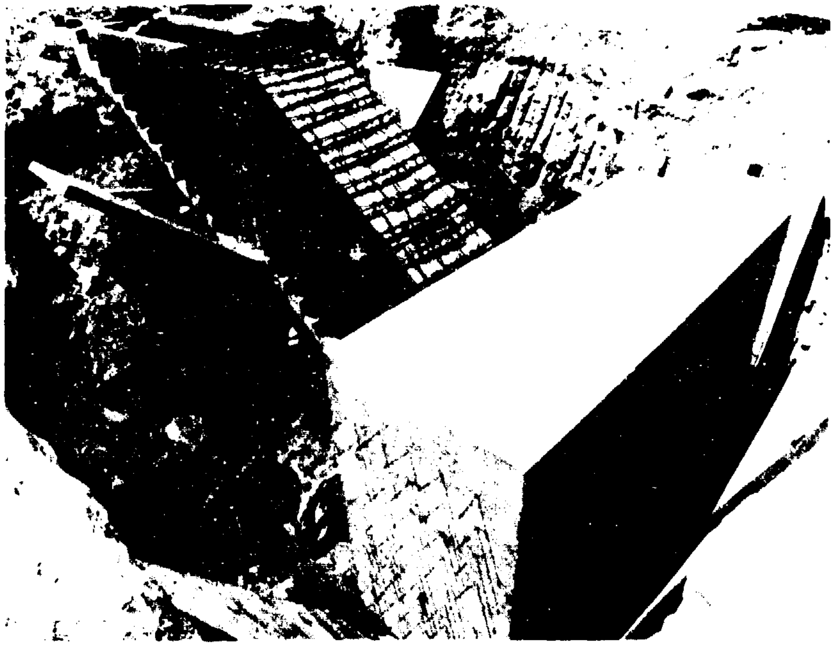

Figure 2.8. Reinforcement of stairwell walls; underground chamber complete.

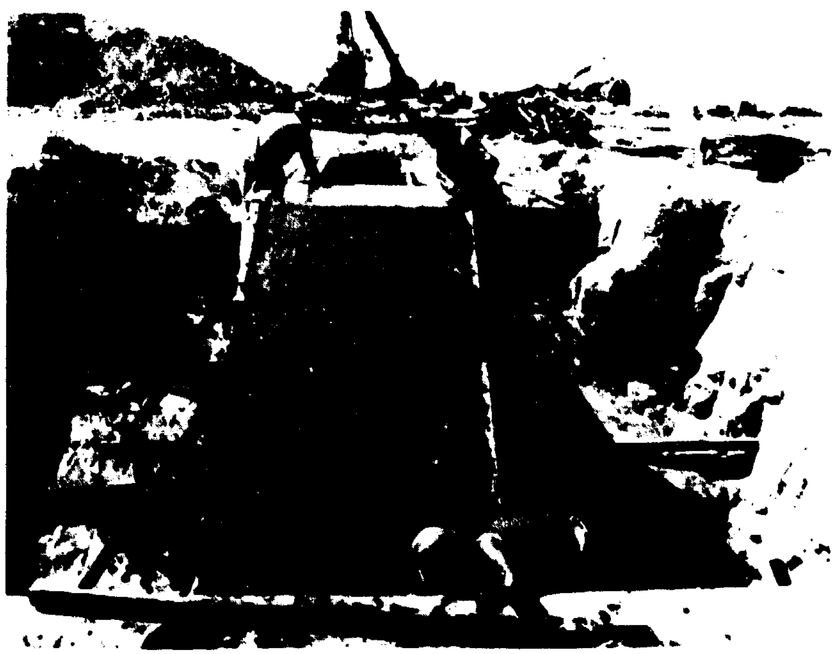

Figure 2.9. Finishing concrete in stairwell roof.

Figure 2.10. Backfill placement around completed structure.

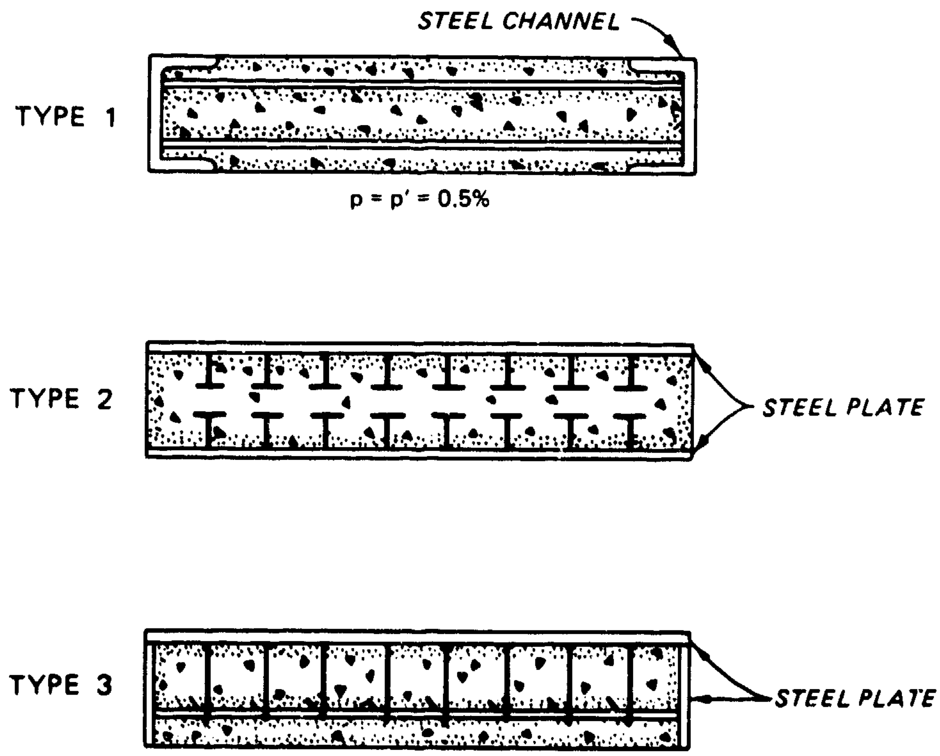

Figure 2.11. Blast door configuration concepts.

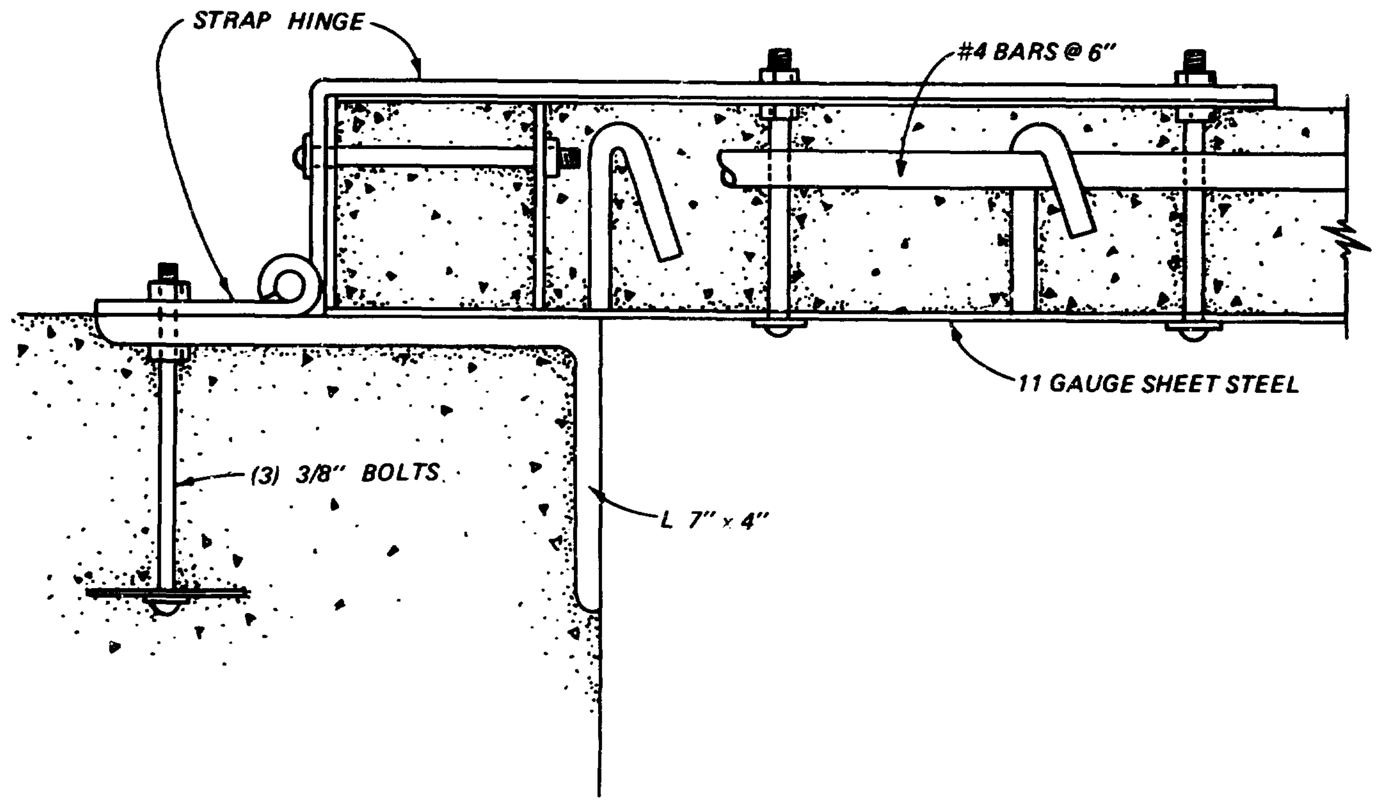

Figure 2.12. Blast door strap hinge details.

Figure 2.13. Blast door shell prior to concrete placement.

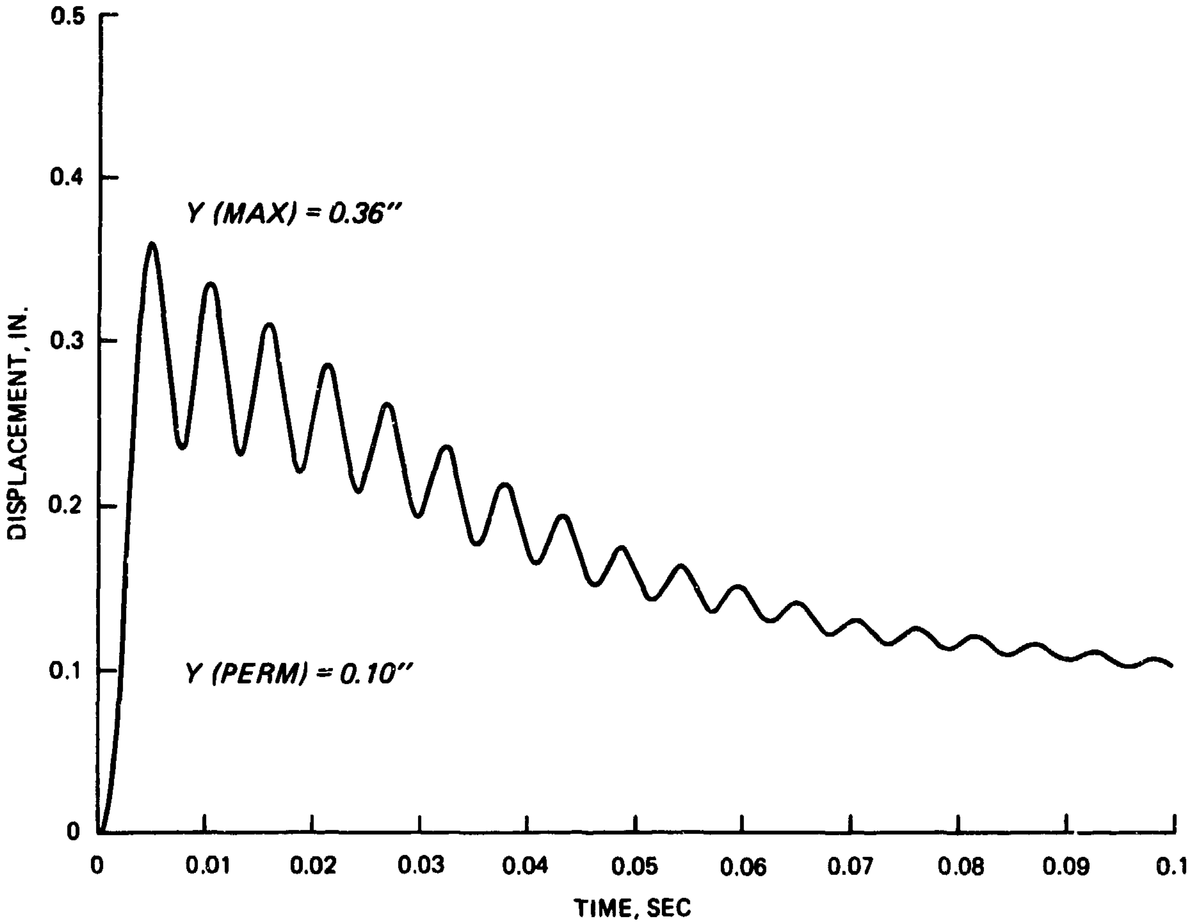

Figure 2.14. Pretest blast door response prediction.

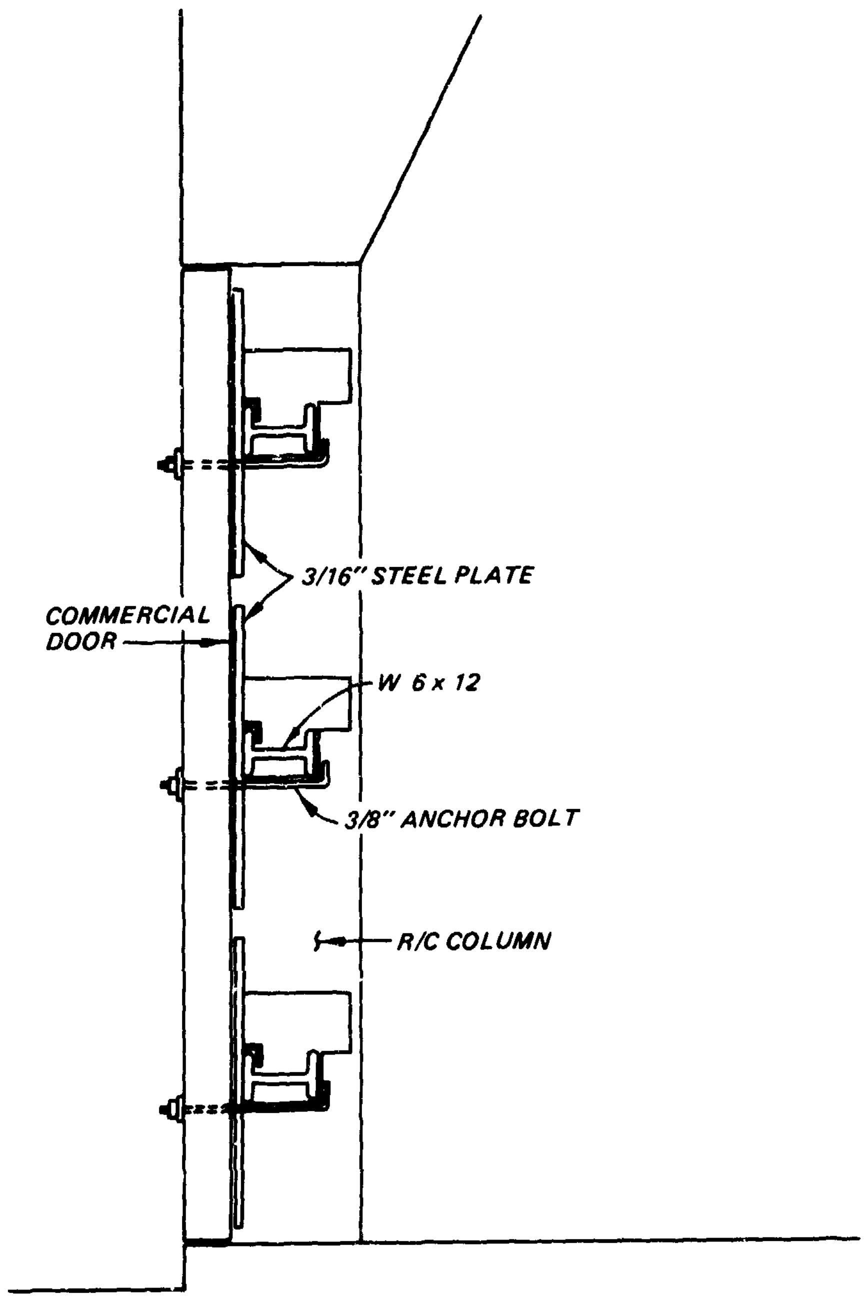

Figure 2.15. Cross section of commercial door and supports.

Figure 2.16. Commercial door (on left, open)
with support beams in place.

Figure 2.17. Commercial door (on left, open) with support plates in place.

Figure 2.18. 1/10-scale models.

CHAPTER 3

EXPERIMENTAL PROCEDURE

3.1 DIRECT COURSE

The DIRECT COURSE event was a high-explosive (HE) test sponsored by the DNA in October 1983. A simulated nuclear weapon airblast and ground motion environment were provided by the detonation of 609 tons of an ammonium nitrate-fuel oil (ANFO) mixture at a height-of-burst of 166 feet. The airblast effects from the detonation of 609 tons of ANFO are approximately equivalent to the airblast effects from the detonation of a 1-KT nuclear device or the detonation of 500 tons of TNT.

The explosive charge was placed in a spherical fiberglass container, 35 feet in diameter, and suspended from a rigid steel column. A photograph of the charge tower assembly is shown in Figure 3.1.

3.2 TEST PLAN

The entryway test structure was constructed and instrumented during June-August 1983. After construction and instrumentation were completed, backfill was placed in 1-foot lifts around the structure up to the existing ground level. Backfill material consisted of a sandy clay. A photograph of the entryway and models in place prior to the test is shown in Figure 3.2. The closures are shown in Figures 3.3 and 3.4.

Figures 3.5-3.7 are instrumentation plans showing all airblast gages used in the test. The airblast gage behind the commercial door, No. P-8, was rendered inoperable prior to the test when its cable was severed during construction. Hence no airblast data are available for the area behind the commercial door. The airblast gages were Kulite V5 92 pressure gages with a maximum range of 200 psi.

Figure 3.1. DIRECT COURSE charge tower assembly (closure and entryway test in foreground).

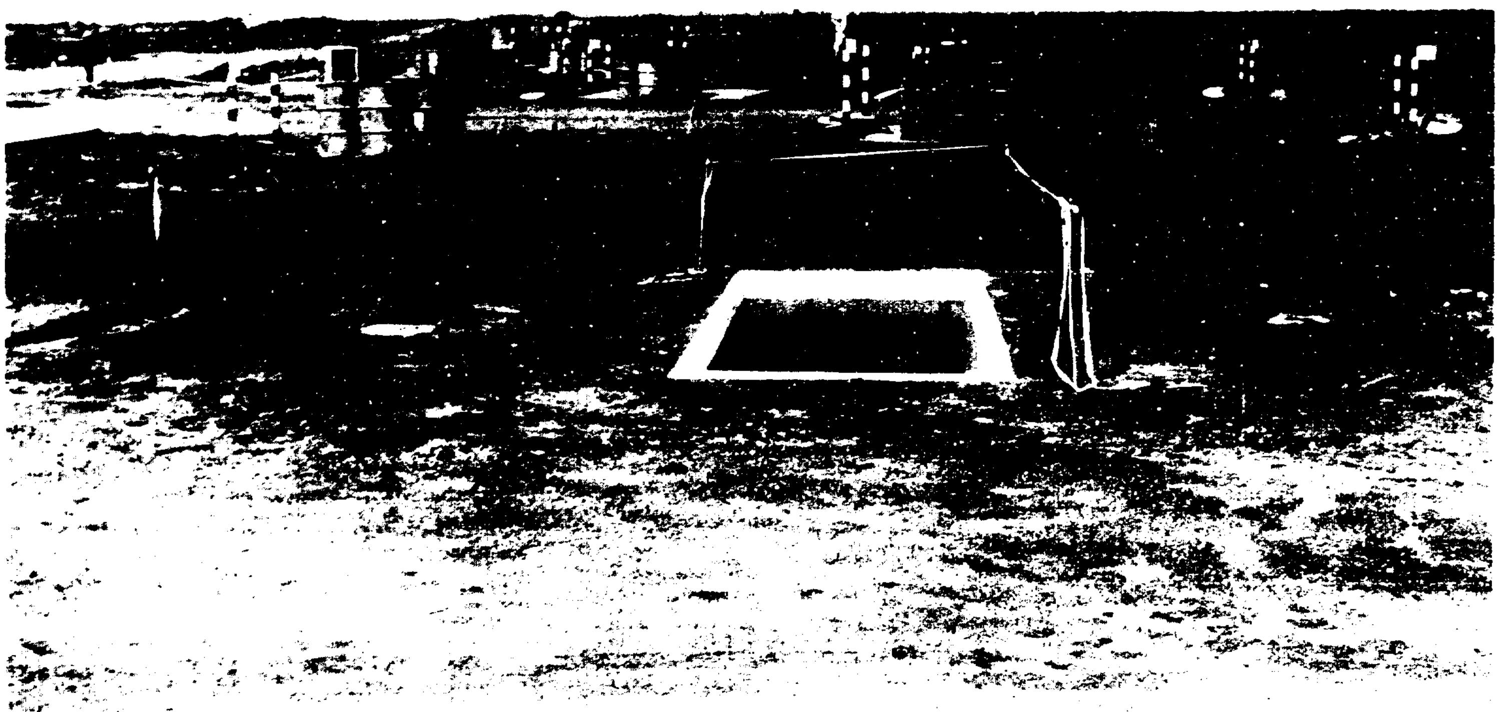

Figure 3.2. Pretest photograph of site layout (1/10-scale models in ground to either side of full-scale structure).

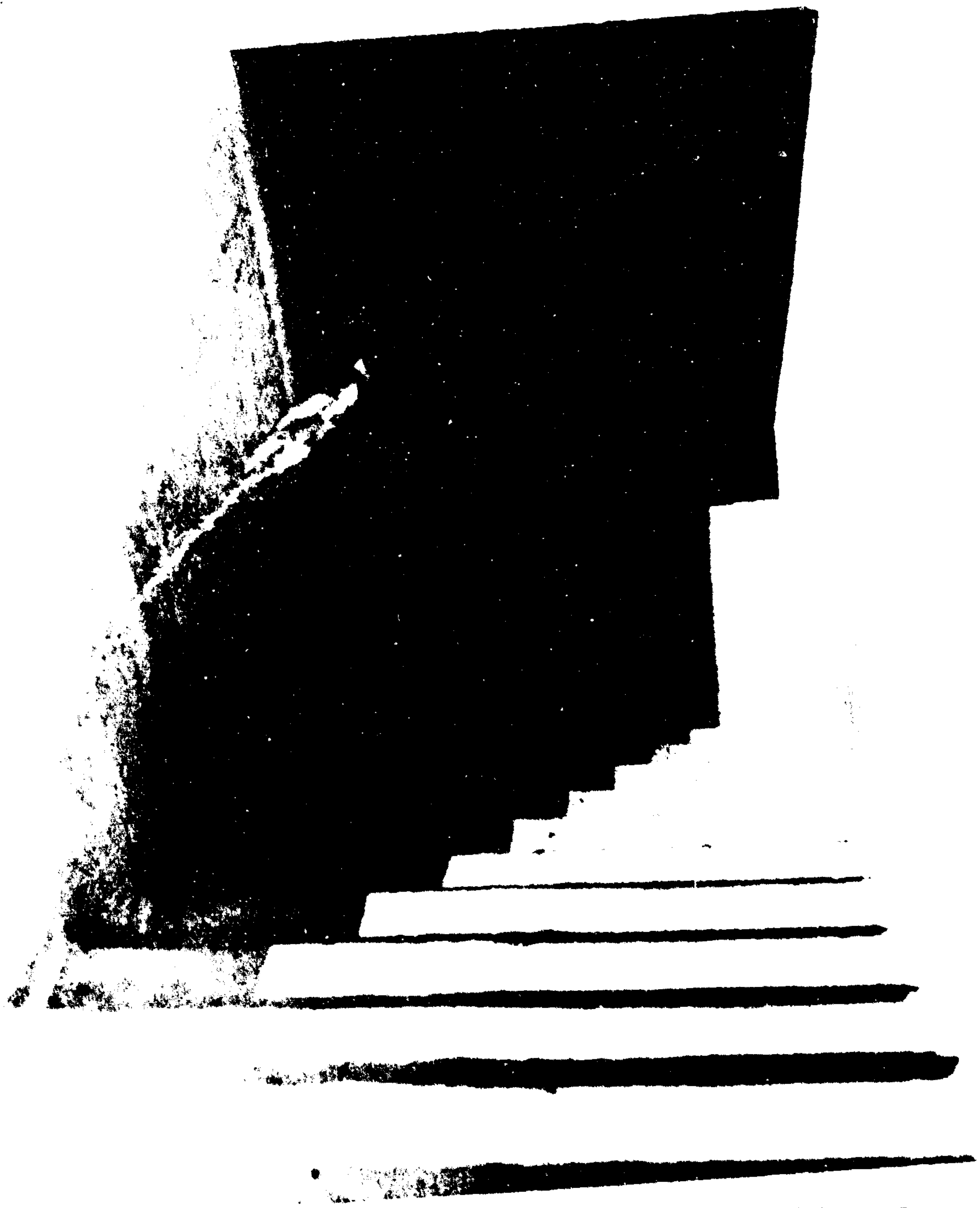

Figure 3.3. Surface view of full-scale entryway (closures on left and right at bottom of tunnel).

Figure 3.4. Reinforced concrete blast door in place.

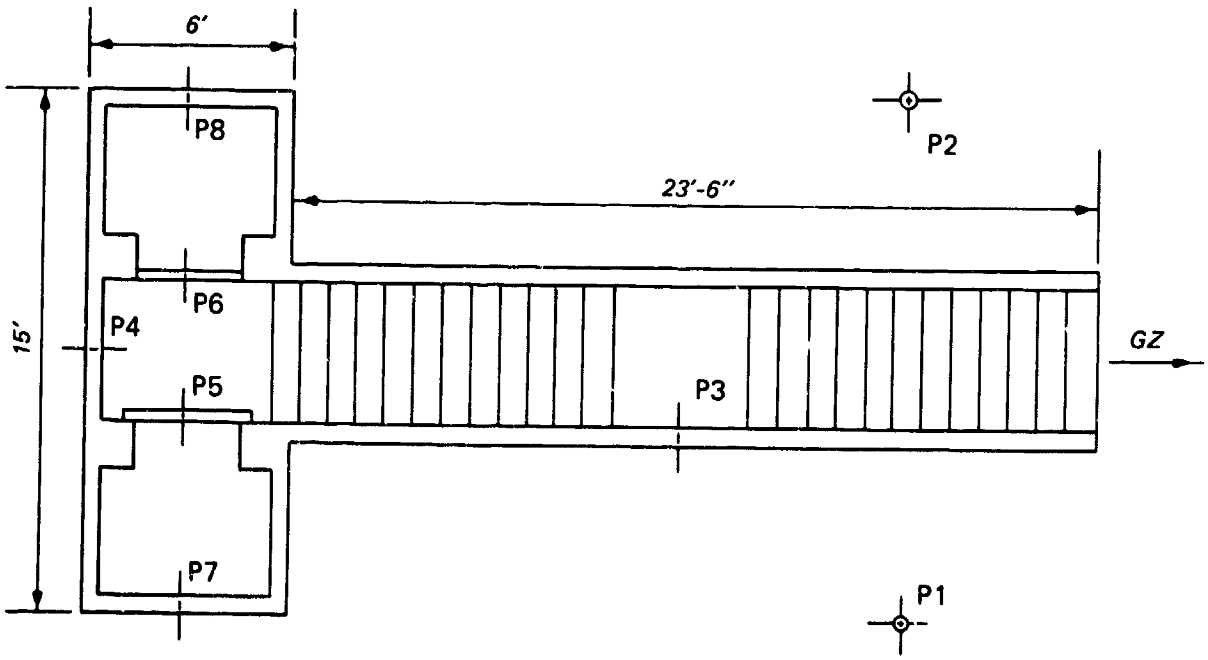

Figure 3.5. Instrumentation of full-scale structure.

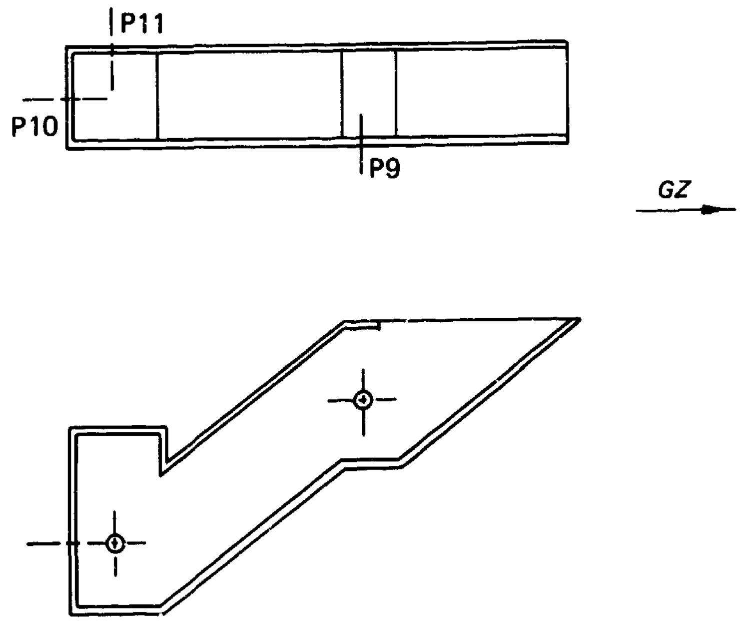

Figure 3.6. Instrumentation of dead-end tunnel 1/10-scale model.

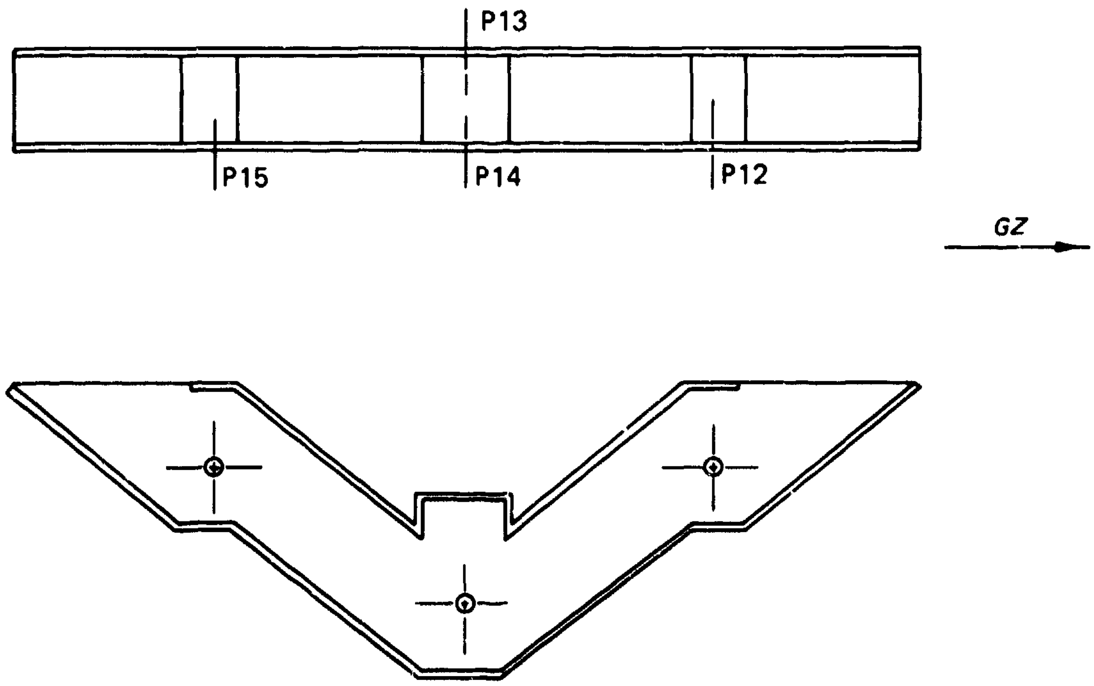

Figure 3.7. Instrumentation of pass-through tunnel 1/10-scale model.

CHAPTER 4

RESULTS

4.1 DATA DISCUSSION

All airblast data were recorded on magnetic tape and later reduced to digital format. A "sample and hold" technique was used to digitize the data. For digitizing, data records were started at the time of detonation. Each of the pressure records was divided into 200,000 uniform time steps per second and sampled at the end of each step.

The location of the test structure was at a higher-than-predicted pressure level. Two surface-flush gages at ground level, P1 and P2, recorded an average maximum overpressure of 69 psi. Hence the pressures recorded inside the entryway were also higher than those predicted. The maximum pressures recorded on the entryway end wall and on the blast door were 180 psi and 159 psi, respectively.

Complete pressure records for each of the airblast gages are shown in Appendix A. Gage P8 was inoperable prior to the test. Zero time on each of the records is the time of detonation.

4.2 STRUCTURAL RESPONSE

Although the roof and walls of the entryway suffered cracking and some permanent deflections, there was no structural failure. The stairwell walls had large cracks along the roof and floor joints, and smaller vertical cracks along their height. The end wall, which received the most severe loading, suffered the most damage. Large cracks formed from the floor to the roof along each wall/door support joint. The end wall was displaced a maximum of about 2 inches on the east edge and 1-1/2 inches on the west edge. The roof exhibited minor cracking along its entire length but was largely undamaged. A posttest surface view of the entryway is shown in Figure 4.1. Wall and roof damage are shown in Figures 4.2 and 4.3.

Upon examination, the blast door showed no signs of damage. The exterior concrete face of the door was intact and had no cracks. The seal surrounding the door's edges was slightly deformed but was not torn. The pressure record from gage P7, immediately behind the door, indicates that there were no pressure leaks at the door's edges. The door's hinges were undamaged and the door

could be easily opened and closed again, as shown in Figure 4.4. The center of the door had a permanent deflection of about 0.18 inch (the door was checked for distortion prior to the test).

The commercial door was completely destroyed during the test. The door and each of the steel plates supporting it were bent around the wide-flange beams, so that large gaps were left between door and frame at either end of the door. As shown in Figure 4.5, the door was obviously inoperable. One of the steel support plates is shown in Figure 4.6. The pressure records for gages P5 and P6 should have been nearly identical, had the commercial door survived. However, comparison of the pressure records for these gages seems to indicate that the commercial door failed very early (about 10 ms after initial loading).

The 1/10-scale models were intact after the test and showed no signs of displacement or rotation. The amount of dust and dirt that accumulated in the models during the test was insignificant.

4.3 STATIC TEST

Static loading of a typical blast door section was conducted at WES to examine the mode of failure of the blast door when loaded to failure. The test specimen was a typical 18-inch-wide section taken from the door's width and was tested as a one-way slab, simply supported, subjected to a two-point loading.

A longitudinal crack formed from the left edge of the test section to the left load point on the top surface of the test specimen very early in the test. When loaded to approximately 24,000 pounds, a diagonal crack formed on the left end of the test section, and the slab abruptly failed (Figure 4.7).

As seen in Figure 4.7, the slab failed in diagonal tension, an undesirable mode of failure. The static test indicated that additional shear reinforcement near the door supports would be needed to insure ductile behavior at high overpressures.

The equivalent uniform load necessary to cause the same moment at the center of the test section due to a two-point load of 24,000 pounds is approximately 49.4 psi. The equivalent uniform load necessary to cause that same moment at the center of the full-scale door, simply supported on all four sides, is only 57 psi. The calculations are obviously not in agreement with

the measured results of the DIRECT COURSE event, where the door survived a pressure of 159 psi.

The initial concrete cracking in the test slab was probably due to a lack of confinement at the edges of the slab, which is not a problem in the full-scale door. How much influence, if any, this initial crack had on the final results of the static test is hard to determine. The conclusion drawn from this test is that the shear reinforcement should be modified in the full-scale door to insure a ductile mode of failure.

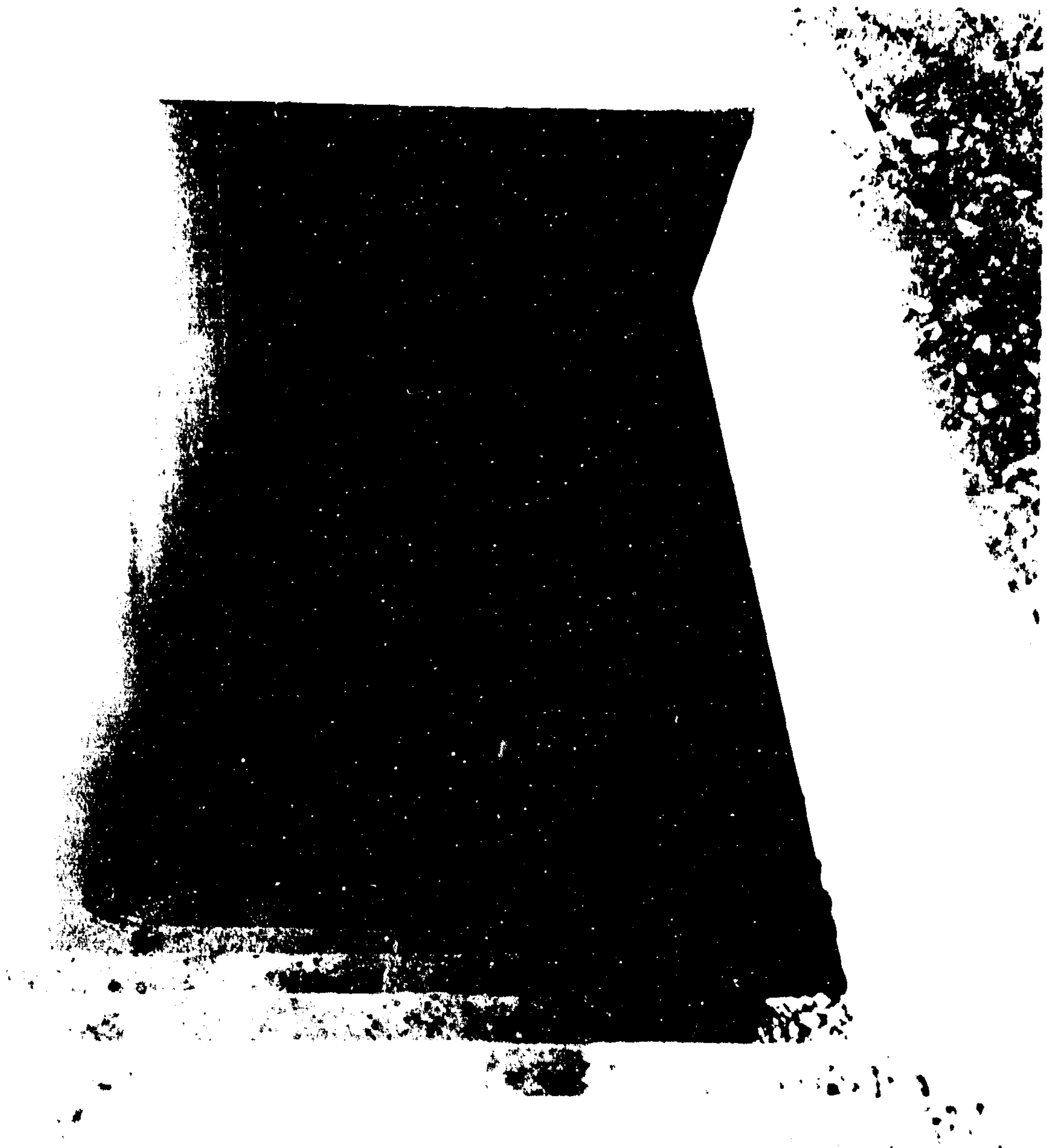

Figure 4.1. Posttest surface view of entryway.

Figure 4.2. Damage to stairwell roof immediately above landing.

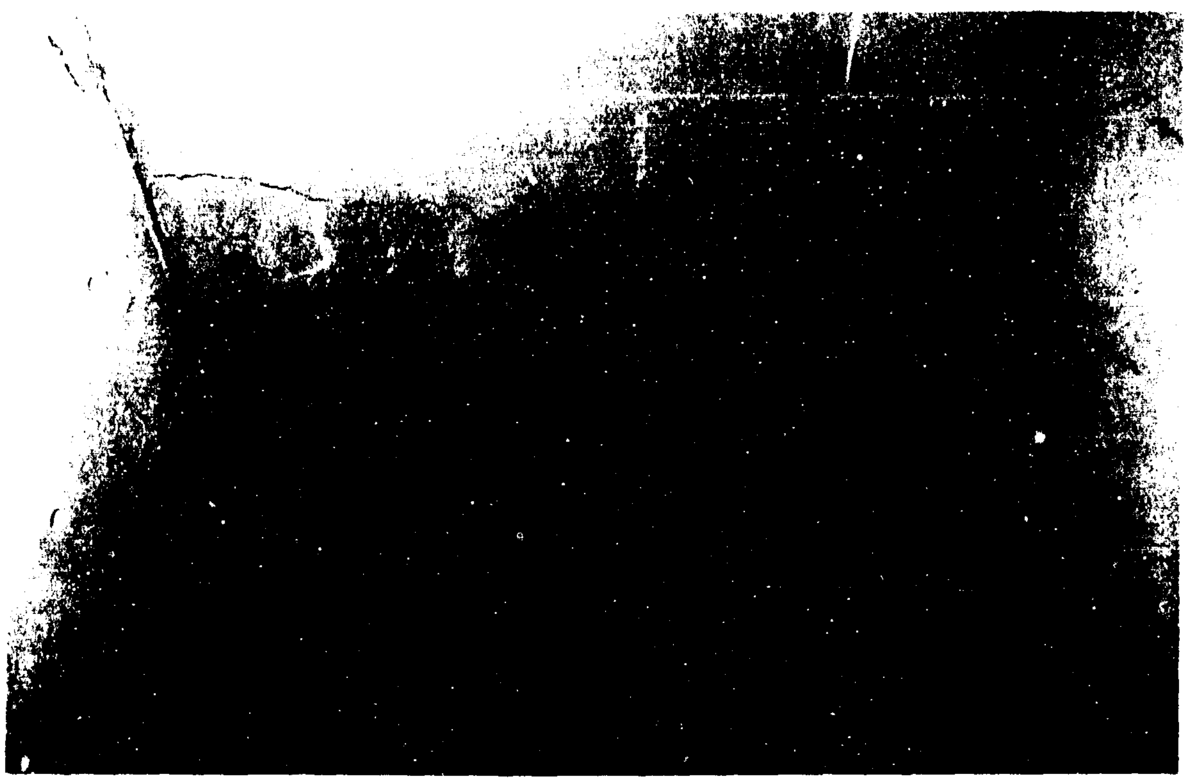

Figure 4.3. Damage to stairwell roof.

Figure 4.4. Closures, reinforced concrete blast door on left, open, commercial door on right.

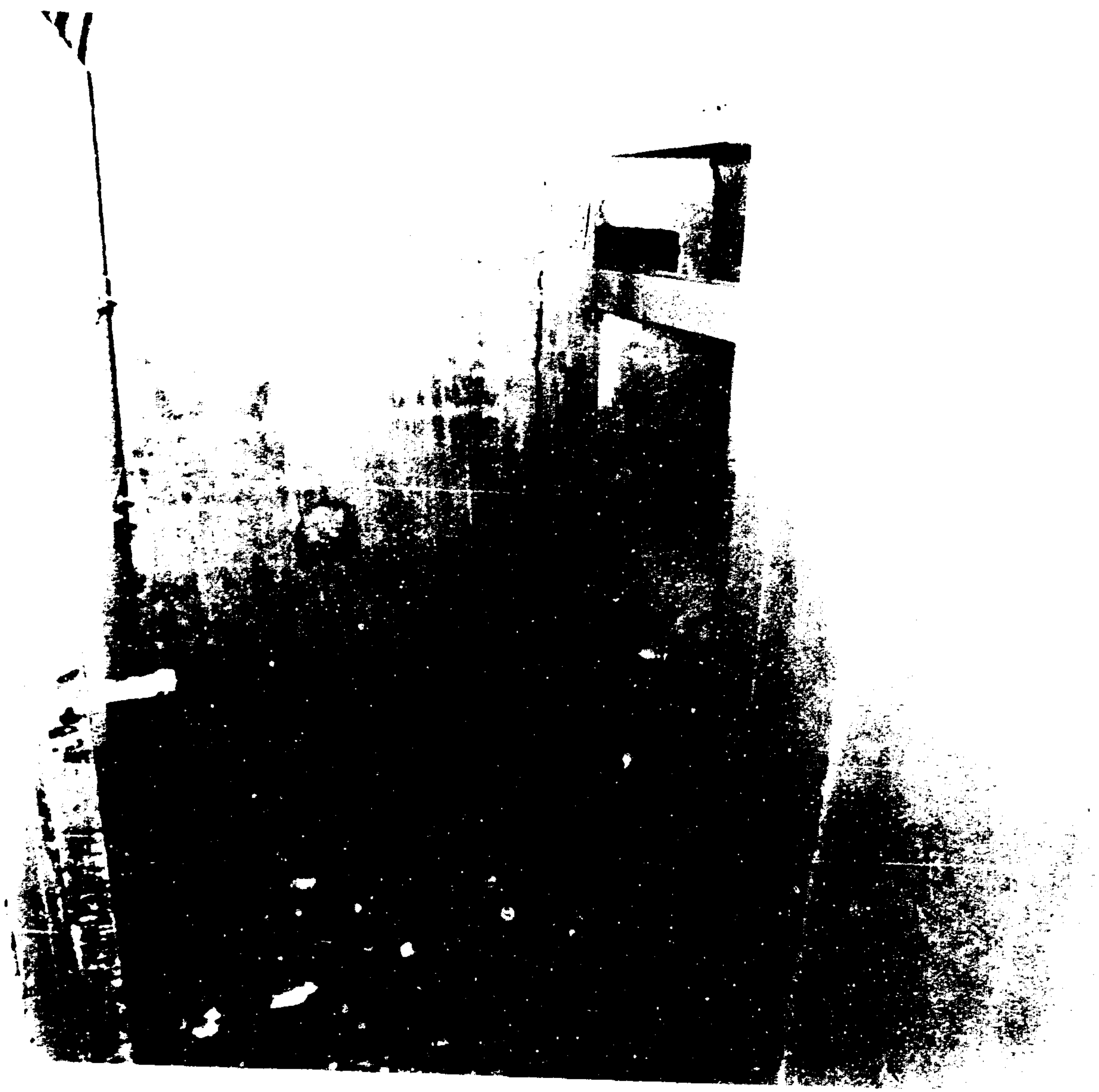

Figure 4.5. Closures, reinforced concrete blast door on left, commercial door on right.

Figure 4.6. Damage to commercial door support plate.

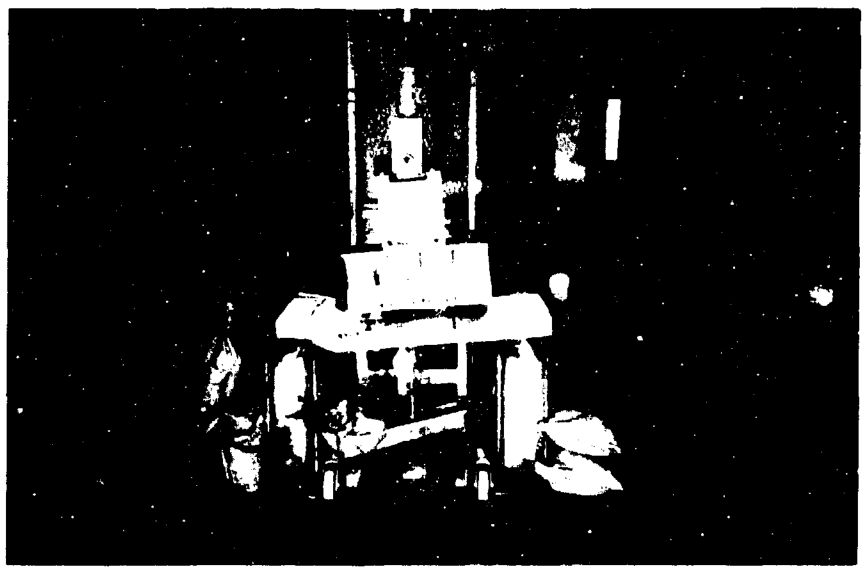

Figure 4.7. Failure of test slab; static test.

CHAPTER 5

ANALYSIS

5.1 VERIFICATION OF PREDICTIONS

5.1.1 Airblast

Since the pressures recorded at the tunnel entrance were higher than those predicted, the measured internal entryway pressures were also higher than the initial predictions. Revised internal pressures were calculated based on the measured pressure data at the tunnel entrance with the following input parameters:

Peak pressure	=	69 psi
Positive phase duration	=	107 ms
Impulse	=	1.48 psi-s

Comparisons of posttest pressure calculations with actual recorded data are tabulated below:

Airblast Gage	Actual Peak Pressure, psi	Calculated Peak Pressure, psi
P4	180	166
P5	159	158
P10	185	235
P11	153	235
P13	65	75

The results of these calculations show close agreement between measured and calculated pressures for the full-scale structure and the pass-through 1/10-scale model, while the calculated pressures for the closed-end model were overpredicted. Calculated positive durations were also reasonably close to the measured values (Figure 5.1).

Comparison of calculated and measured pressures inside the entryway gave assurance that input parameters for the design event (1 MT, 50 psi) would yield a reasonable estimate of the airblast record inside the entryway during that event.

5.1.2 Blast Door Response

Since the peak pressure on the blast door was higher than that predicted, the response of the blast door would be expected to be slightly more severe than pretest calculations indicated. A single-degree-of-freedom response

analysis[15] was again performed for the blast door with the airblast record from the center of the door input as the loading function. For this analysis, the door was considered lightly damped (3 percent of critical damping). Results of this analysis are shown in Figure 5.2. The calculated maximum response of the door was 0.45 inch at 8 ms after the door was initially loaded, resulting in a ductility of about 1.7 and a permanent deflection of about 0.18 inch. Recall that the measured permanent deflection in the door was also about 0.18 inch.

Since both the internal pressure calculations and the blast door response predictions compare favorably with the measured data, response predictions due to other weapons and/or pressures should approximate the response with little error.

5.2 PREDICTING RESPONSE TO OTHER WEAPONS/PRESSURES

The DIRECT COURSE event provided a 1-KT simulated nuclear airblast environment from which response and pressure predictions could be verified. However, survival of structural elements in a 1-KT environment does not guarantee survival in a 1-MT environment at the same overpressure level. Airblast predictions for a 1-MT, 50-psi event were necessary to verify the survivability of the blast door in that environment.

Internal tunnel pressures were calculated for a 1-MT, 50-psi event with the following input:

Peak pressure	=	50.0 psi
Positive phase duration	=	964 ms
Impulse	=	12.4 psi-s

The predicted loading history for the blast door is shown in Figure 5.3. The calculated peak pressure on the door is 165 psi. Note that this peak pressure is substantially higher than the peak pressure of 142 psi predicted for the 1-KT, 50-psi overpressure level at the DIRECT COURSE event. This is because the airblast associated with a 1-KT event decays much more rapidly than the airblast from a 1-MT event at the same overpressure level. Hence, the incident pressure at the closed end of the entryway will be higher for a 1-MT event than for a 1-KT event, and the reflected pressures at the same point will be higher by an even larger margin.

Response calculations for the blast door were performed with input from Figure 5.3, with the following results:

Maximum deflection	= 0.55 inch	
Ductility, μ	= 2.0	(see Figure 5.4)
Permanent deflection	= 0.28 inch	

These calculations indicate that the blast door will sustain very light damage and should remain completely serviceable when subjected to a 1-MT, 50-psi airblast environment. (Recall that the calculated ductility from the DIRECT COURSE event was about 1.7.)

Although the blast door will survive the airblast effects of a 1-MT, 50-psi event, a slightly higher surface overpressure with a worst case orientation will cause substantially greater damage. For example, a 1-MT event with a surface overpressure of 60 psi will result in a peak pressure of 204 psi at the blast door with a duration of about 900 ms. As the ultimate resistance of the door is about 180 psi, this load would very probably result in the complete collapse of the door.

When a shock wave strikes the end wall of the dead-end entryway, a reflected pressure is instantly developed on that surface. The magnitude of the reflected pressure varies from about double the applied pressure to greater than a factor of 8 times the applied pressure, depending on the magnitude of the incident pressure. Since the peak reflected pressure acting on the door in a dead-end tunnel is so sensitive to changes in the surface overpressure, it may be desirable to consider a pass-through tunnel system, in which the shock wave is allowed to flow through the tunnel past the closure.

5.3 PASS-THROUGH ENTRYWAY

A pass-through entryway system (Figure 5.5) similar to the 1/10-scale model tested at DIRECT COURSE was evaluated to determine its survivability and cost relative to a dead-end entryway. The ANSWER computer code was used to determine the airblast inside the tunnel.

Airblast calculations indicate that the worst case orientation for a pass-through entryway is with one opening facing ground zero. Comparison of incident to peak pressures for dead-end and pass-through entryways is shown in Figure 5.6.

Response calculations for the blast door in a pass-through entryway were performed for various overpressure levels with the following results:

P_{so}, psi	Peak Pressure on Closure, psi	Calculated Maximum Response of Blast Door in a Pass-Through Tunnel, in.
50	77	0.15
100	142	0.29
130	180	0.44
135	186	1.2
140	192	4.5
150	204	14.5 (probable collapse)

These calculations show that the blast door, when placed in a pass-through entryway, should survive the airblast effects of a peak surface overpressure (P_{so}) of about 135 psi. Survivability of the shelter closure at 135 psi yields a decrease in the lethal radius from ground zero of about 35 percent, or about 1,500 feet. While this difference may seem insignificant, inclusion of a pass-through entryway would obviously provide a beneficial factor of safety for a 50-psi-rated shelter.

A rough cost analysis of the two entryway systems examined indicates that the pass-through entryway could be constructed for an additional 60 percent above the cost of the dead-end entryway. This figure would approach 50 percent if the stairwell formwork is reused on the mirror-image second stairwell.

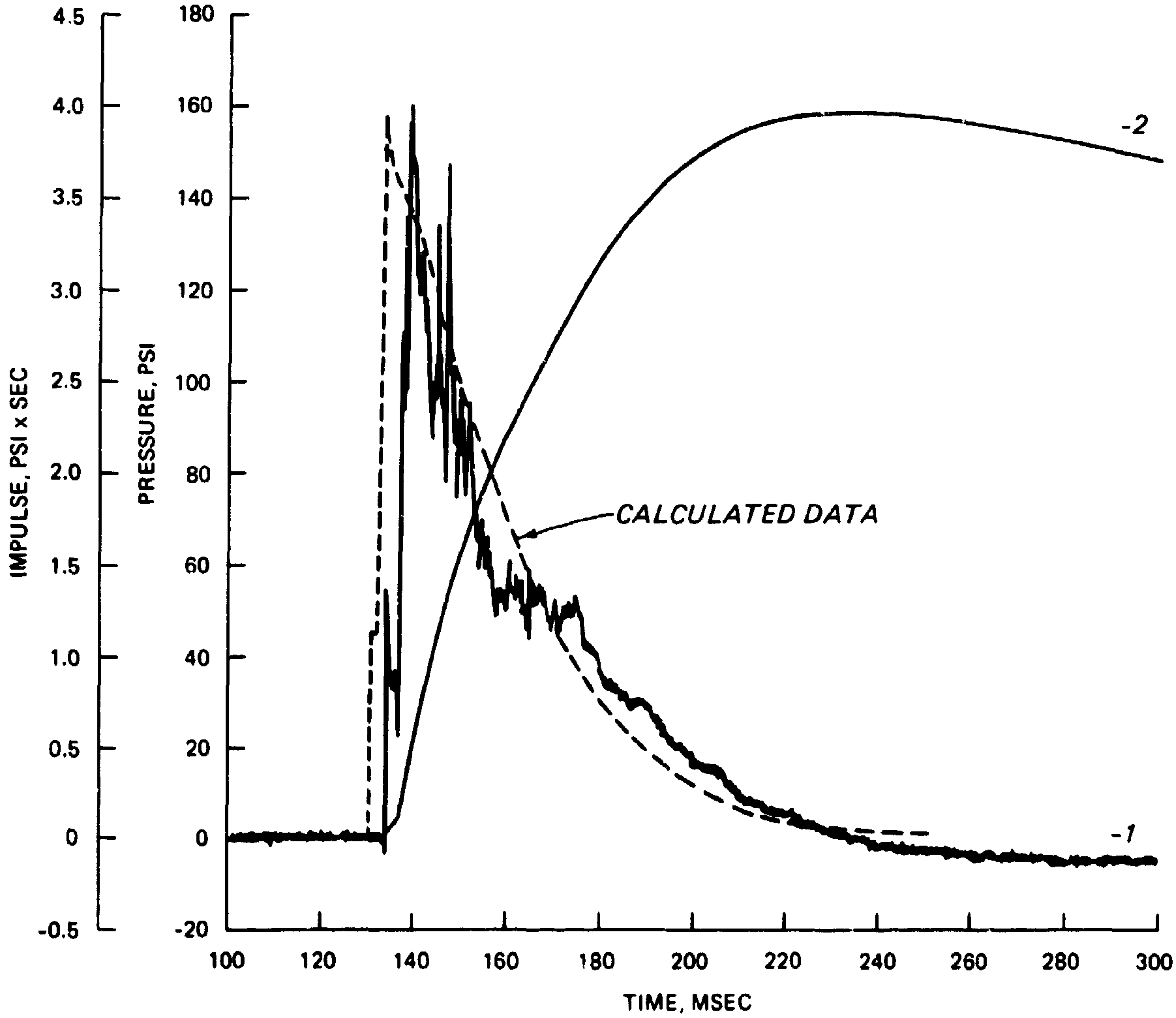

Figure 5.1. Comparison of measured to calculated pressure data for blast door loading.

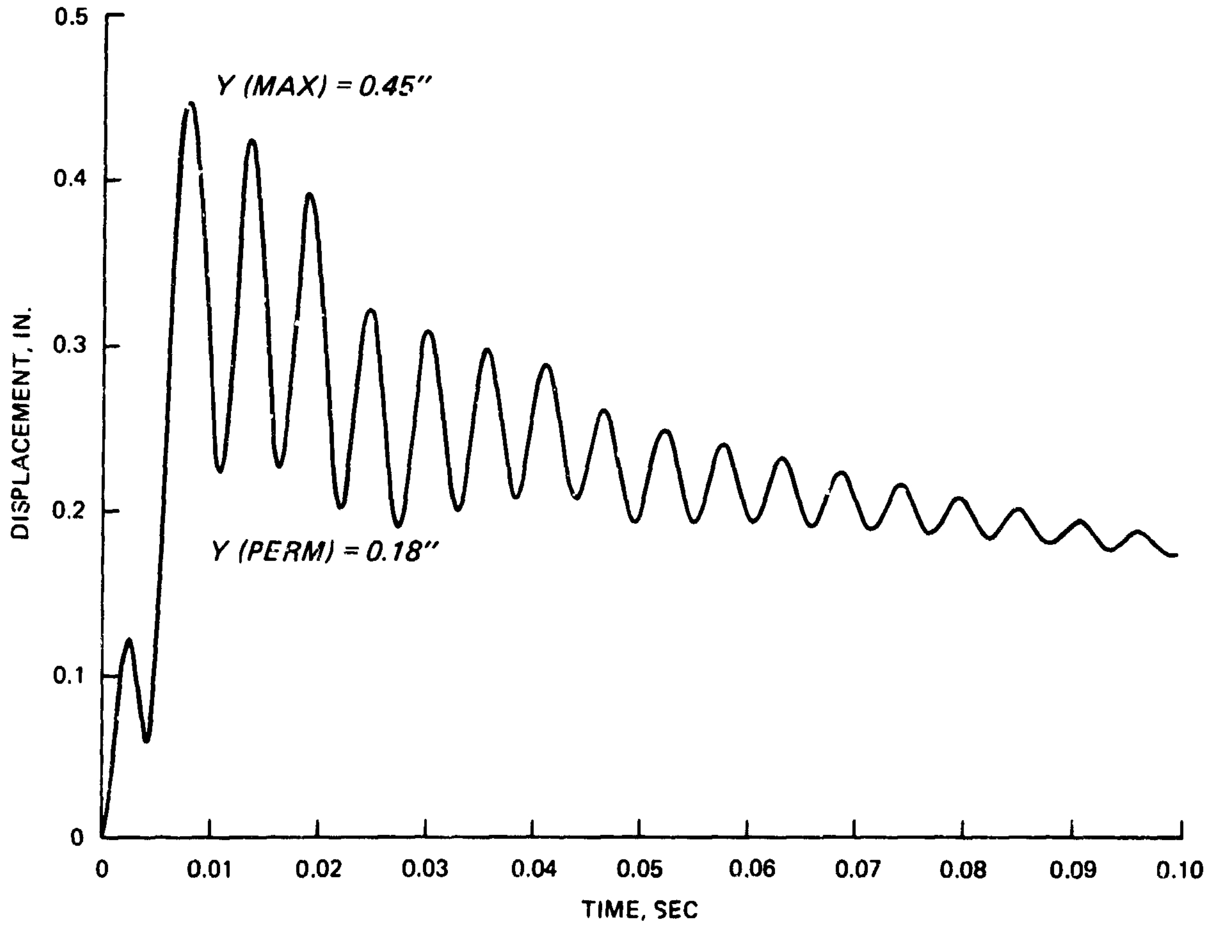

Figure 5.2. Calculated response of blast dooı to DIRECT COURSE loading.

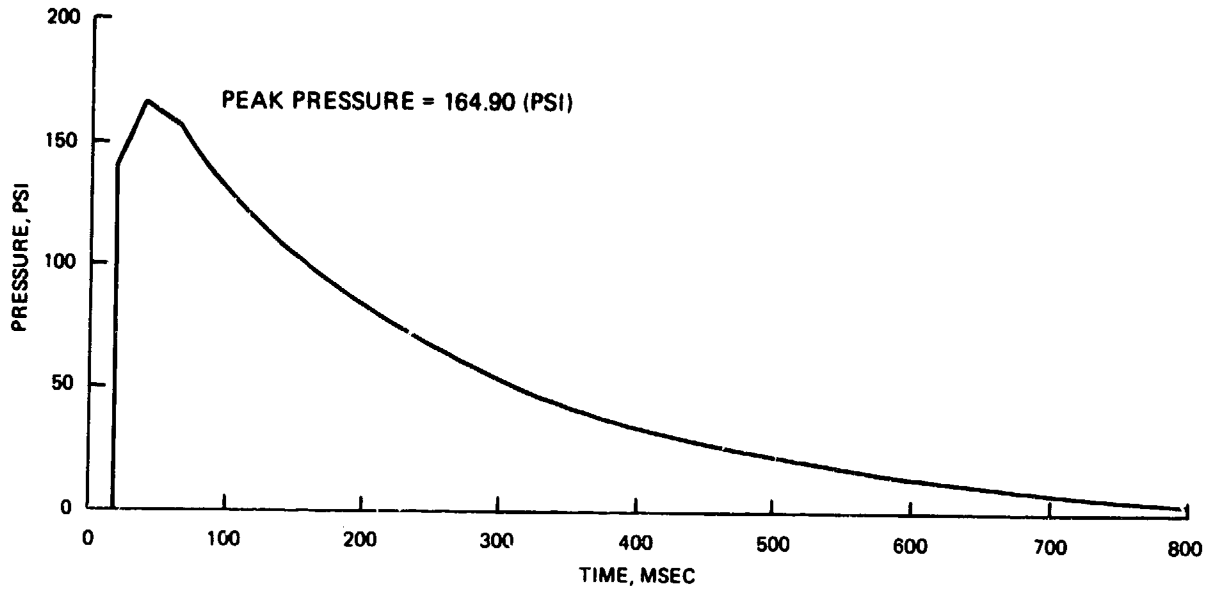

Figure 5.3. Calculated loading history of blast door for 1-MT, 50-psi event.

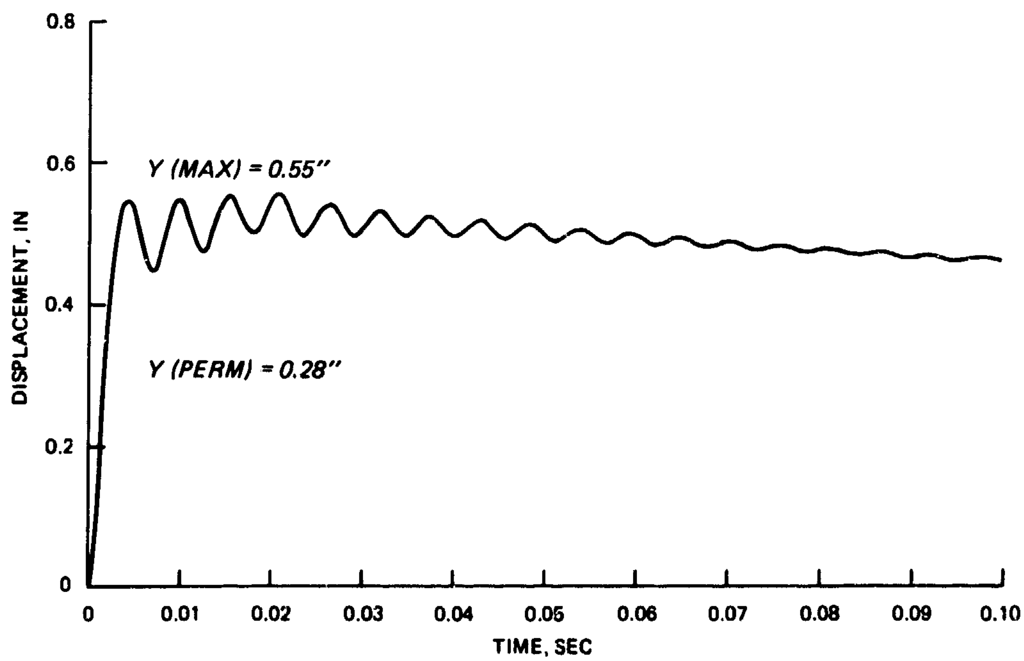

Figure 5.4. Calculated blast door response for 1-MT, 50-psi event.

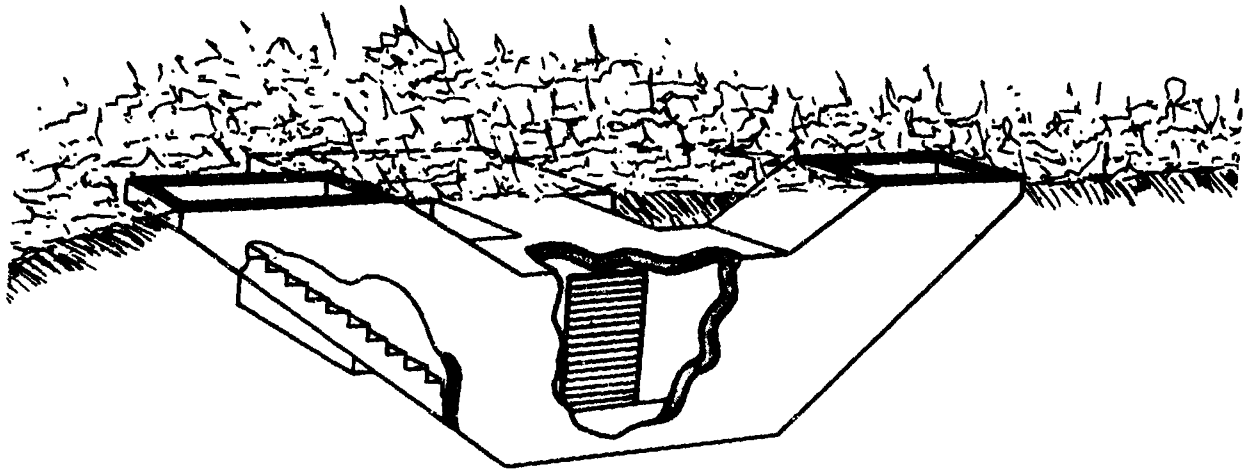

Figure 5.5. Pass-through entryway system.

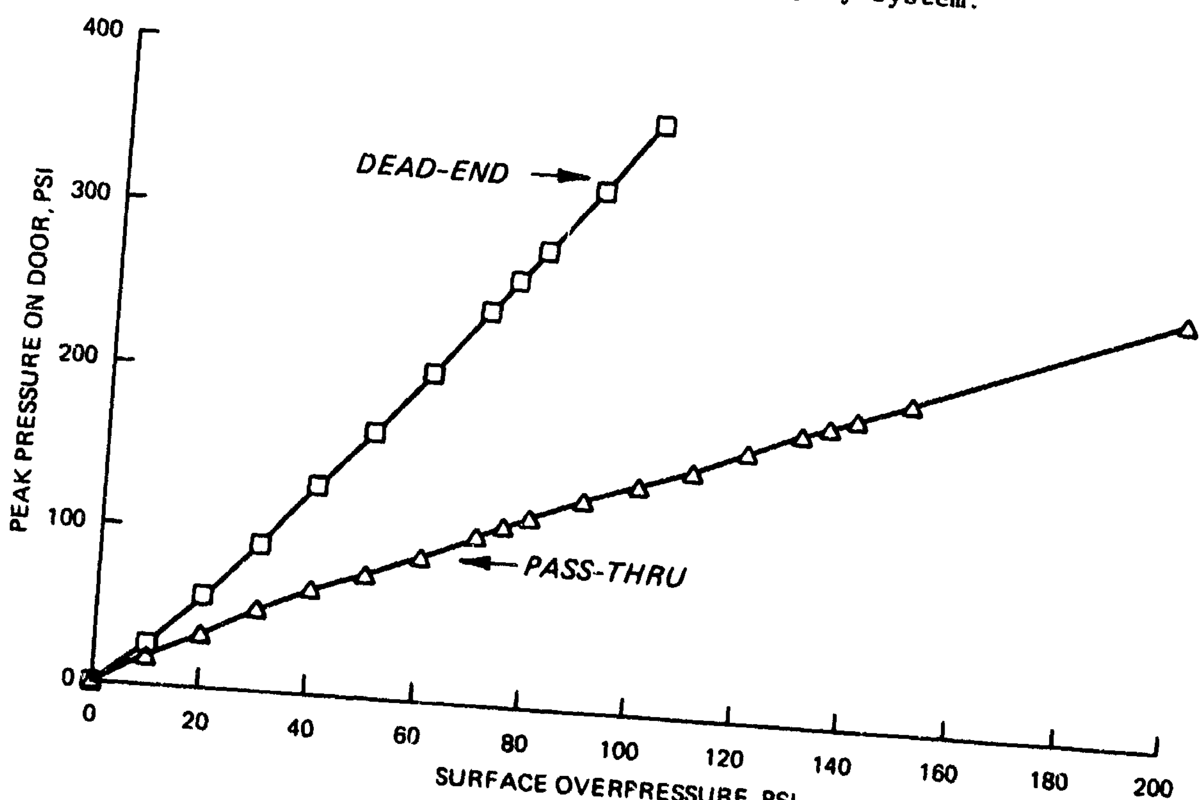

Figure 5.6. Comparison of incident to peak pressure on closure in dead-end and pass-through entryway systems.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The blast door evaluated will successfully withstand peak pressures of about 160 psi, as demonstrated in the DIRECT COURSE event. Since the duration of the airblast from a 1-KT event at the 50- to 150-psi overpressure level is very long relative to the natural period of vibration of the door (about 5.5 ms), the response of the door to a peak pressure of 160 psi should be roughly equivalent to that measured at DIRECT COURSE, regardless of the duration. Hence, the blast door is an adequate design for a 1-MT, 50-psi event when placed in a dead-end tunnel. The blast door evaluated would provide adequate protection from much higher overpressures if used in a pass-through tunnel system, which would allow the blast wave to flow through the tunnel past the closure without striking any large reflecting surfaces. For example, a 1-MT, 135-psi event would result in a peak pressure on the closure of about 186 psi and a maximum door deflection of about 1.2 inches in a pass-through tunnel (compared to 520 psi and collapse in a dead-end tunnel). Existing commercially available doors capable of withstanding 50 to 150 psi range in price from about $5,000 to $51,000 each, while reinforced concrete blast doors could be built for about $1,000 each, or $900 each if purchased in lots of 20 or more.

A static test of an 18-inch-wide typical section from the blast door subjected to a two-point loading indicates a brittle mode of failure. What influence, if any, the lack of confinement at the longitudinal edges of the test specimen had on the failure mode is hard to determine. Additional shear reinforcement should be added to insure ductile behavior of the door at relatively large deflections. If the 3/8-inch bars used as shear reinforcement are replaced by 1/4-inch welded studs with smaller spacings, the shear reinforcement requirements can be met without significantly altering the cost of the door.

The fire-rated door with special supports which was evaluated was a typical commercially available exterior door. Though this door was heavily reinforced with wide-flange beams and steel plates, it was completely destroyed during the DIRECT COURSE event, apparently failing about 10 ms after initial loading. The support beams survived the blast, but the door and steel plates

were unable to support the load between each beam span. A much thicker, and thus heavier and more expensive, steel plate would be required to insure survival of this closure concept. Placement of the supports prior to the test was a cumbersome process and required an undesirable amount of time, especially when considered in the context of an imminent nuclear strike. The cost of the commercial door, door frame, and fabrication of the supports was about $750. With thicker, more expensive, steel plates the door might be made to survive, but the problem of placing the supports would be much worse. At the pressure levels examined in this test, standard commercial doors are not a practical alternative for blastproof shelters.

The entryway wall and roof slabs survived the DIRECT COURSE event with only minor cracking, and the structure remained completely intact. As expected, the greatest damage occurred at the slab joints, since the net effect of the interior and exterior loads was to punch out each corner of the tunnel. In no case was the damage extensive enough to warrant changes in the slab design. The slab design tested, which was 6 inches thick with principal reinforcement consisting of 1/2-inch bars spaced at 12 inches on center, is adequate for a 1-MT, 50-psi event. Higher overpressures would require slightly thicker walls, but this parameter is not as sensitive to changes in peak pressure as might be expected because of the additional strength provided by the soil backfill.

Calculations of airblast in the tunnel were performed with the ANSWER computer code, which was developed in the Explosion Effects Division of the Structures Laboratory at WES. Predicted peak pressures inside the full-scale structure were remarkably close to those measured at the DIRECT COURSE event, and predicted durations and impulses were equally accurate. The ANSWER code has proven to be a valuable tool for predicting airblast characteristics inside a tunnel.

6.2 RECOMMENDATIONS

Based on the results of this project, the following recommendations are made:

1. Given the uncertainties of predicting the airblast associated with nuclear detonations, a pass-through entryway system is recommended over a dead-end tunnel to insure a factor of safety for the shelter closure.
2. Concepts such as the commercial door evaluated in this project should not

be used when the design overpressure is greater than about 25 psi. The cost of upgrading a standard door can be larger than the cost of a reinforced concrete door.

3. Additional static tests of the blast door should be conducted to determine the minimum amount and spacing of shear reinforcement needed to insure ductile behavior.

4. The blast door evaluated is recommended for use in a 50-psi shelter with modifications to the shear reinforcement. For reasons of economy, welded shear studs should be used in place of bent reinforcing steel. These shear studs should be spaced at no more than 1-1/2 inches on center near the door supports to insure ductile behavior at higher overpressures.

5. Shear stirrups may be safely omitted from the entryway walls, but should be included in the roof slabs. A minimal number of stirrups should be used in the walls to keep the principal reinforcement properly aligned during concrete placement.

6. Backfill placement around the entryway should be tightly controlled to prevent excessive outward wall movement.

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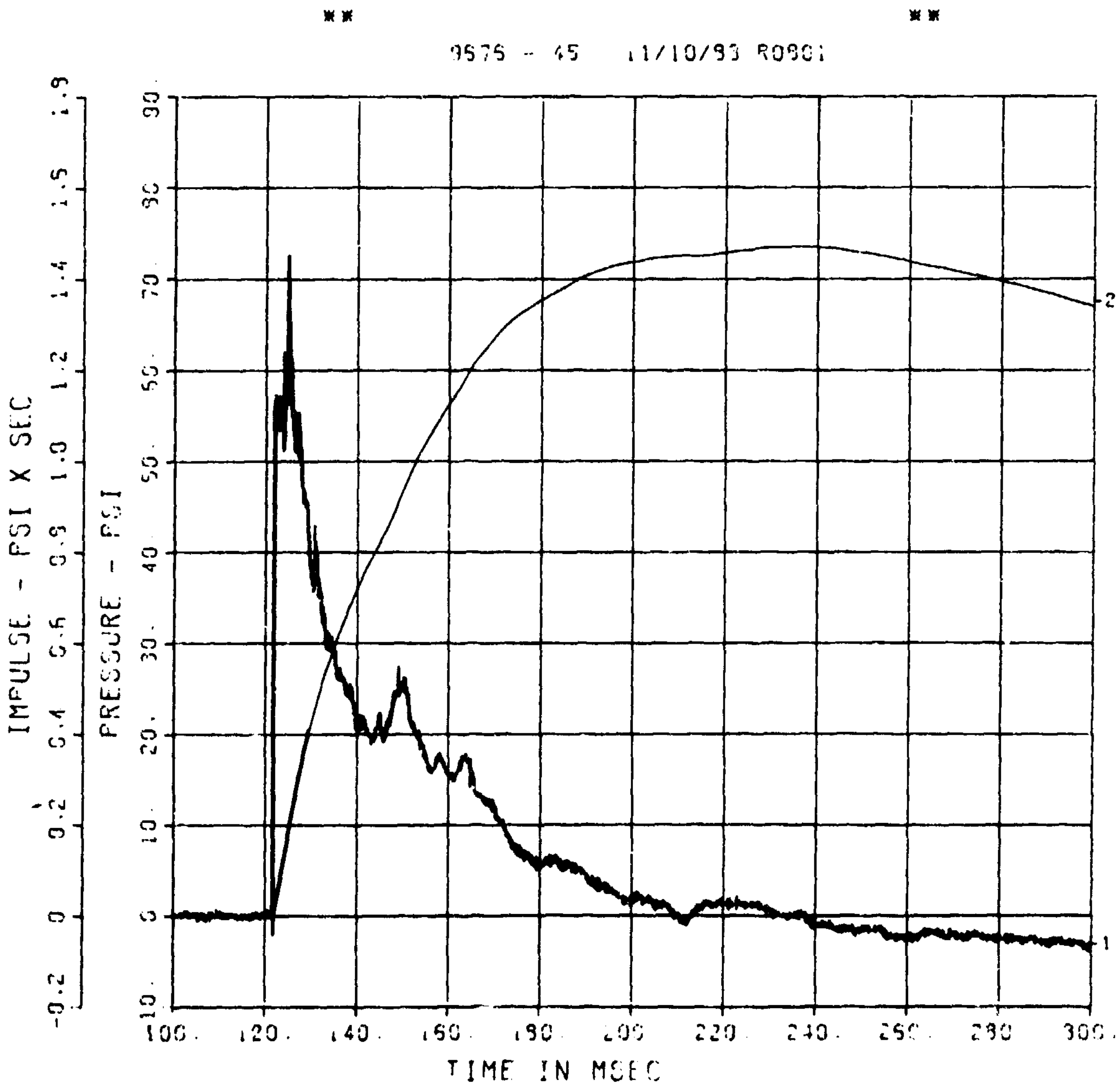
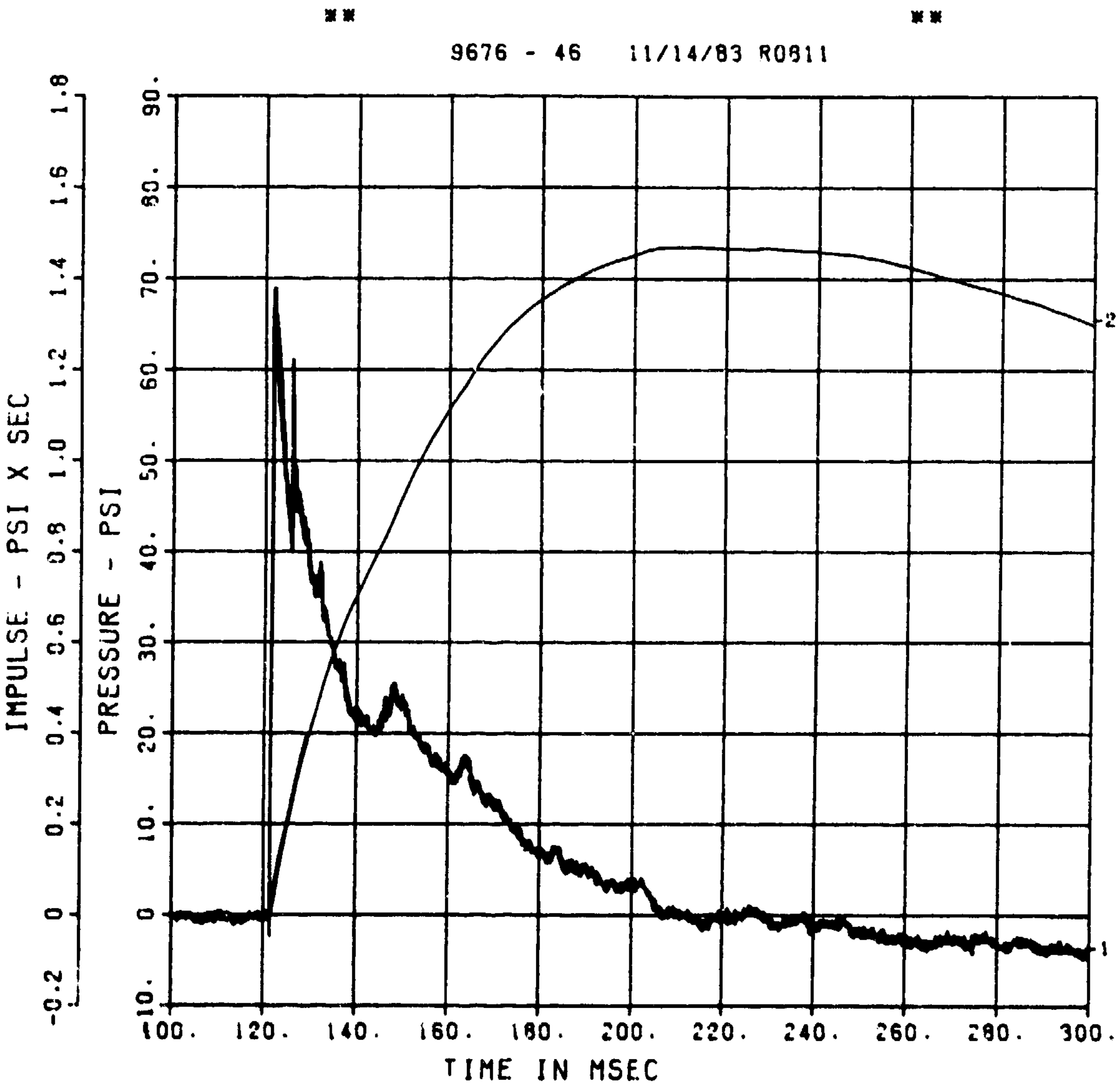
APPENDIX A: PRESSURE DATA

DC ENTRYWAY
P1/4095
200000. HZ CAL= 87.50

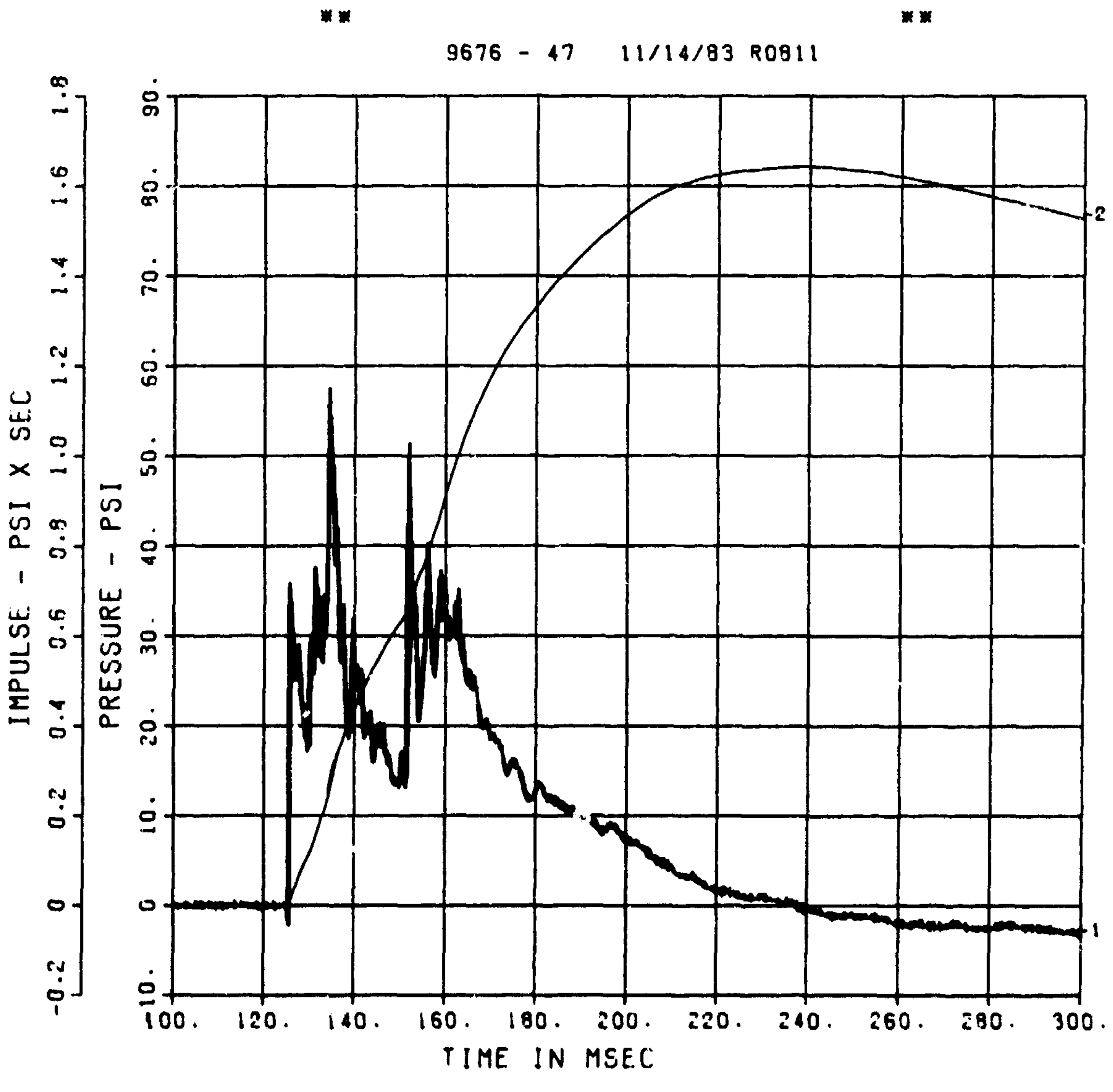
LP3/0 70% CUTOFF= 11000. HZ



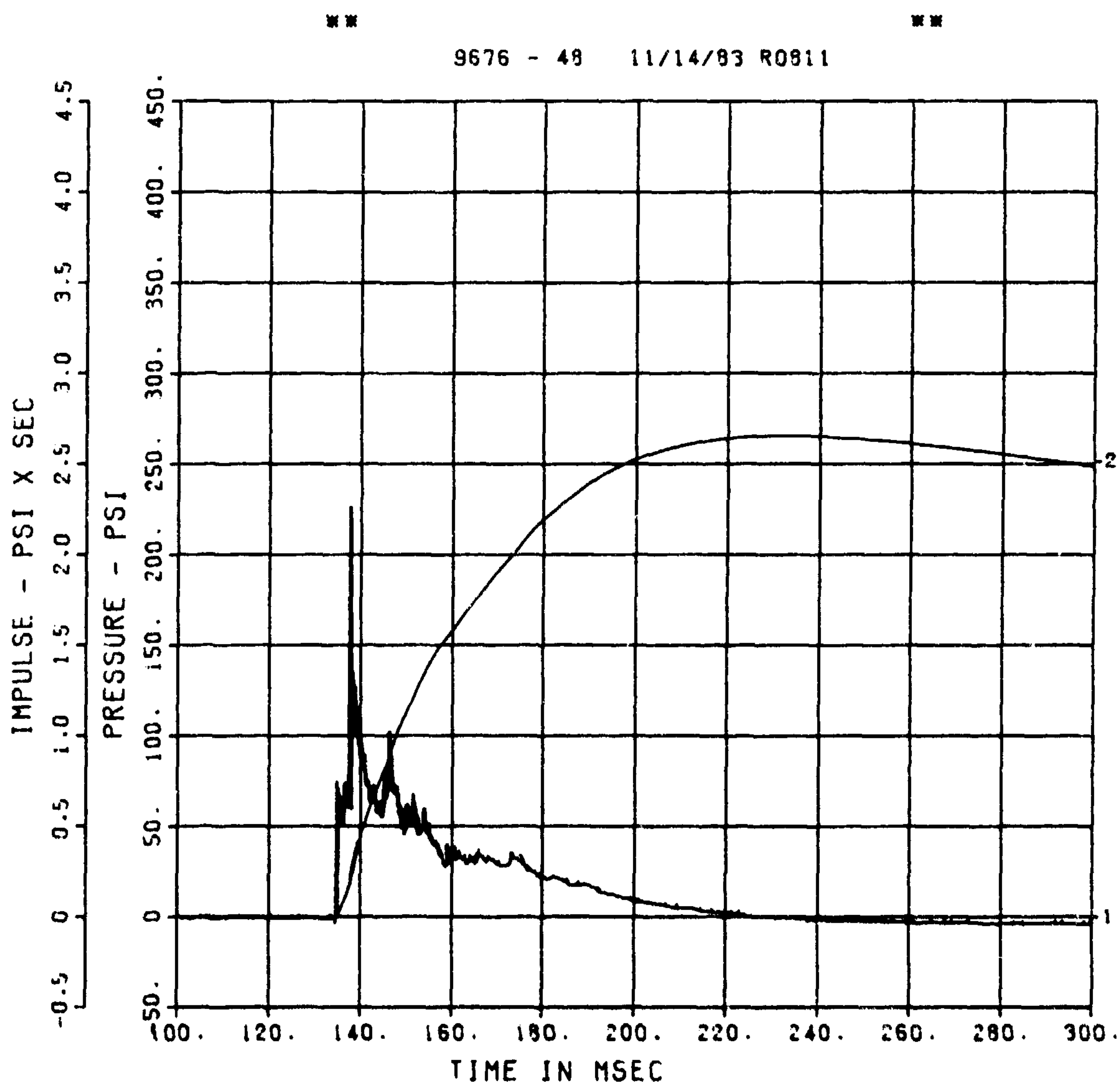
DC ENTRYWAY
P2/4095
200000. HZ CAL= 94.70
LP3/0 70% CUTOFF= 11000. HZ



DC ENTRYWAY
P3/4095
200000. HZ CAL= 76.40
LP3/0 70% CUTOFF= 11000. HZ

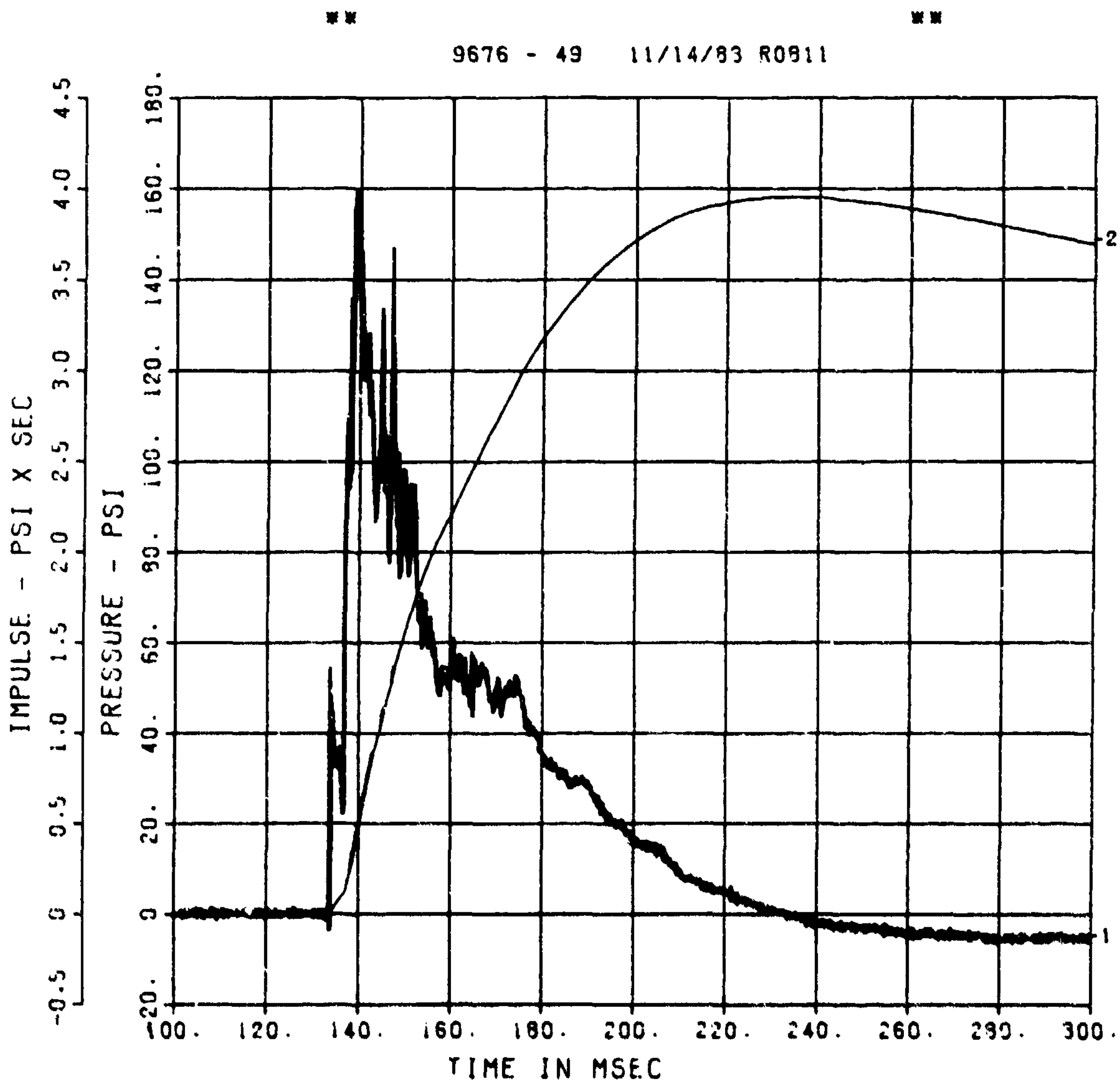


DC ENTRYWAY
P4/4095
200000. HZ CAL= 191.5
LP3/0 70% CUTOFF= 11000. HZ

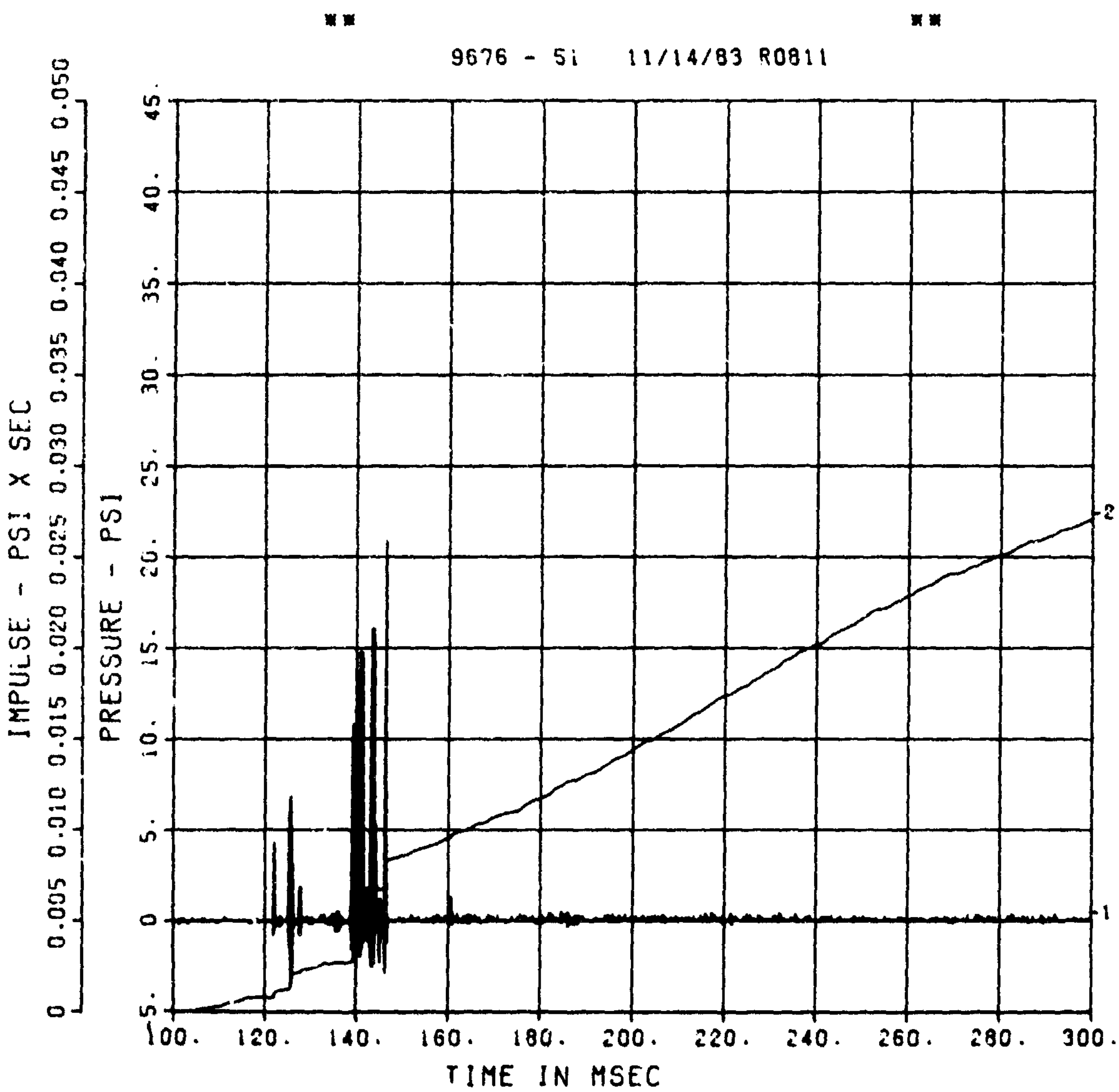


** PEAK VALUE IS 18 % OVER CALIBRATION **

DC ENTRYWAY
P5/4095
200000. HZ CAL= 196.3
LP3/0 70% CUTOFF= 11000. HZ



DC ENTRYWAY
P7/4095
200000. HZ CAL= 9.980
LP4/0 70% CUTOFF= 9000. HZ



** PEAK VALUE IS 109 % OVER CALIBRATION **

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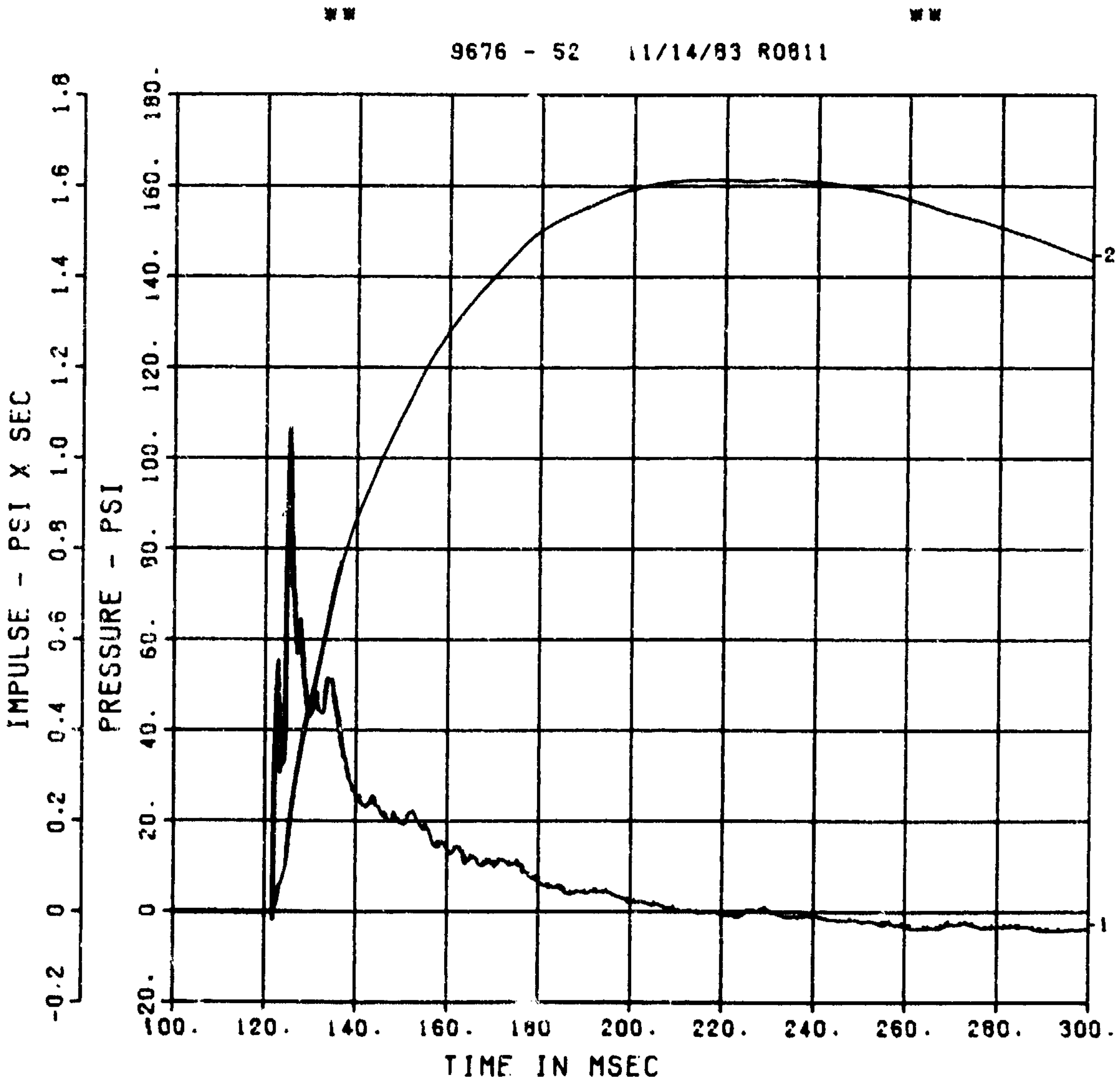
LP3/0 70% CUTOFF= 11000. HZ



** PEAK VALUE IS 24 % OVER CALIBRATION **

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P10/4095
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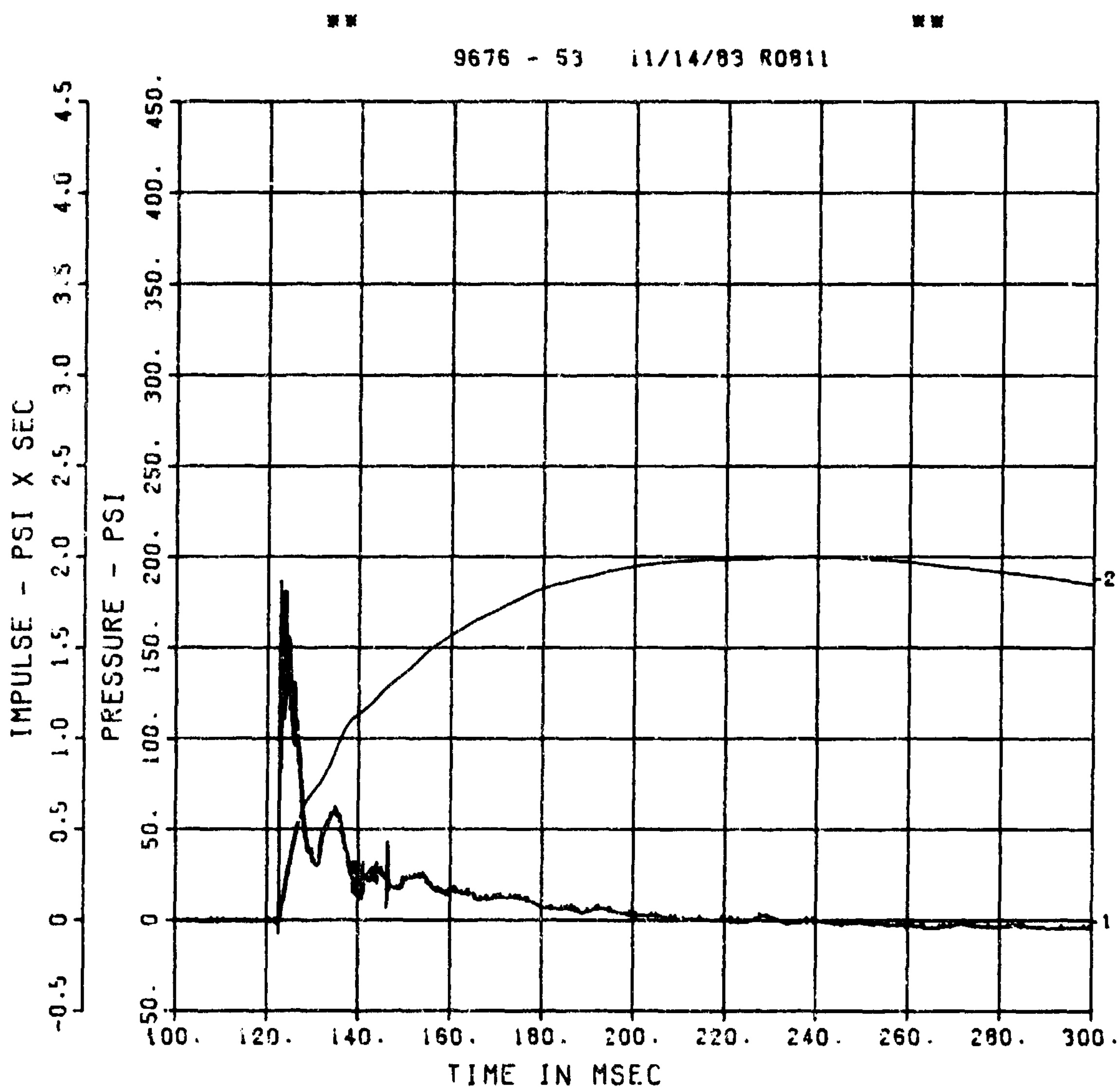
LP3/0 70% CUTOFF= 11000. HZ



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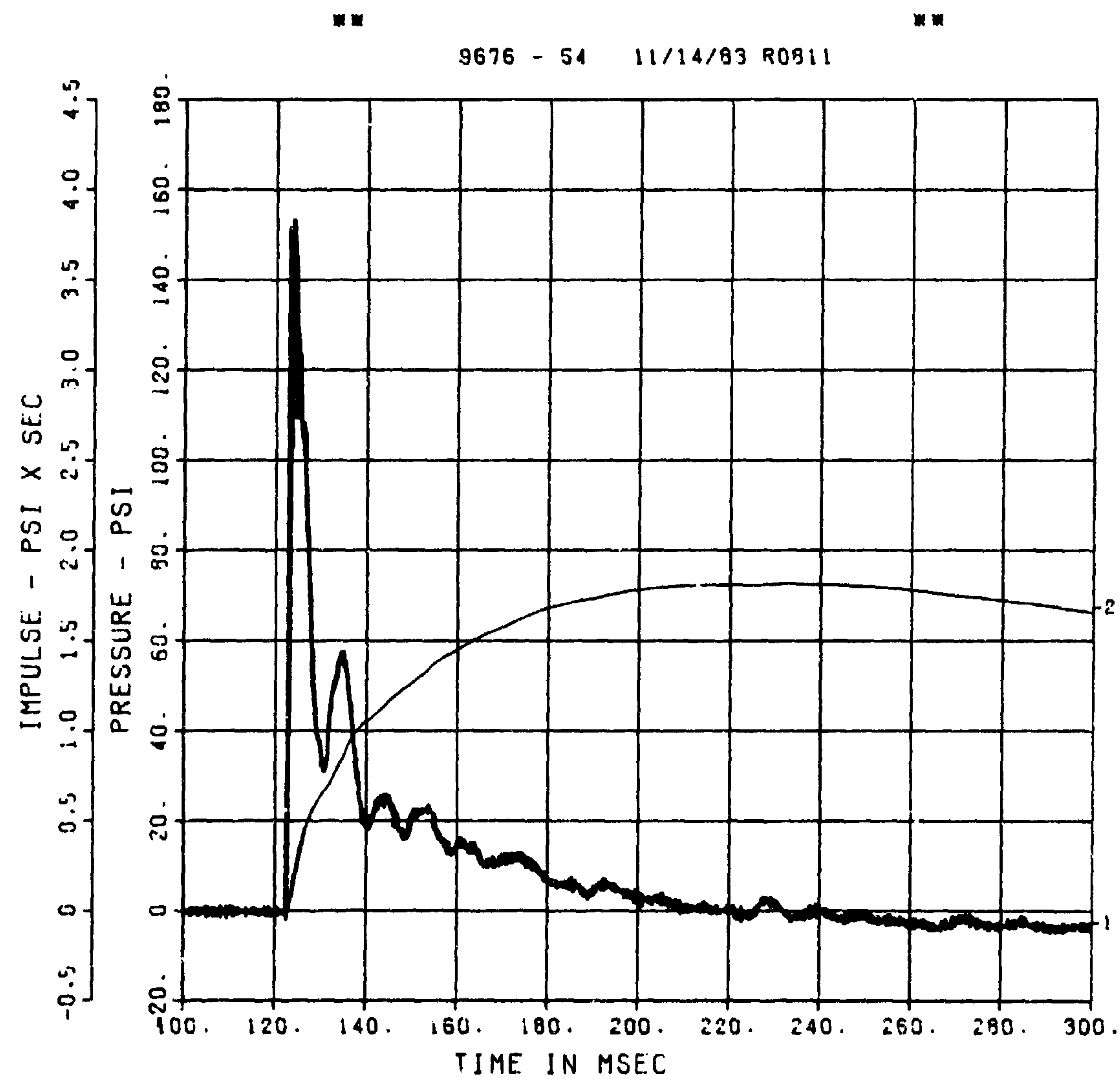

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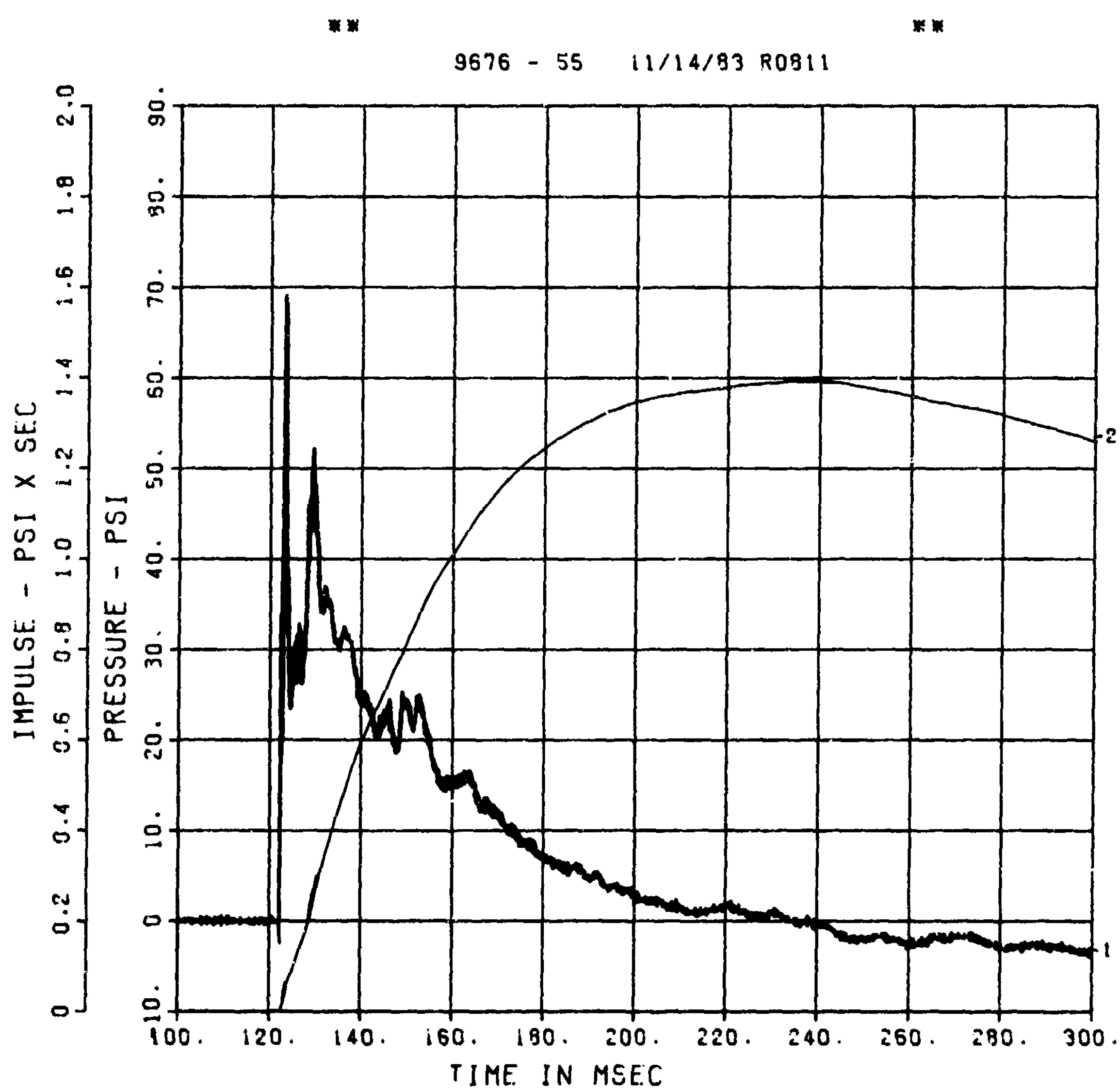
LP3/0 70% CUTOFF= 11000. HZ



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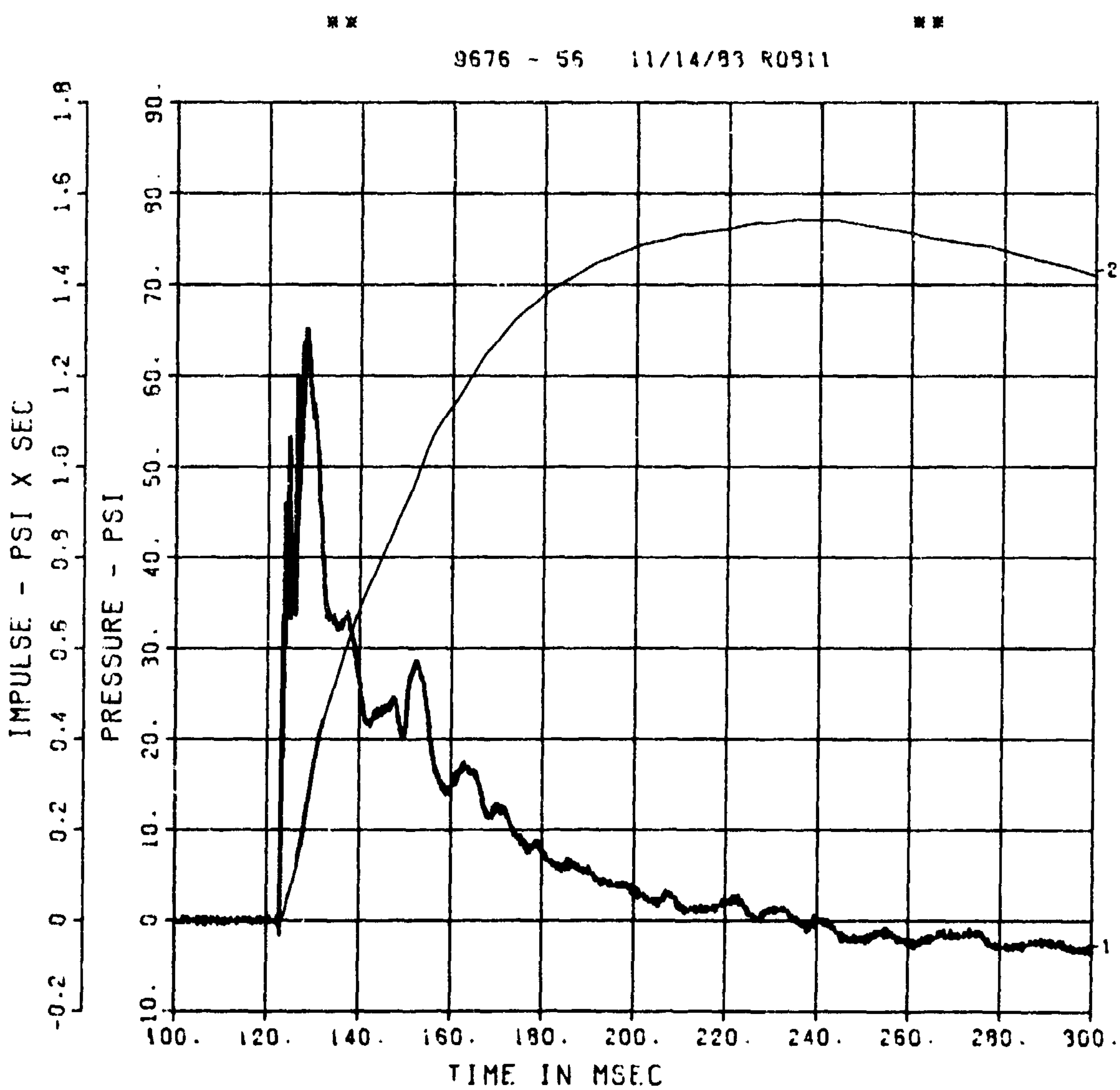
LP3/0 70% CUTOFF= 11000. HZ

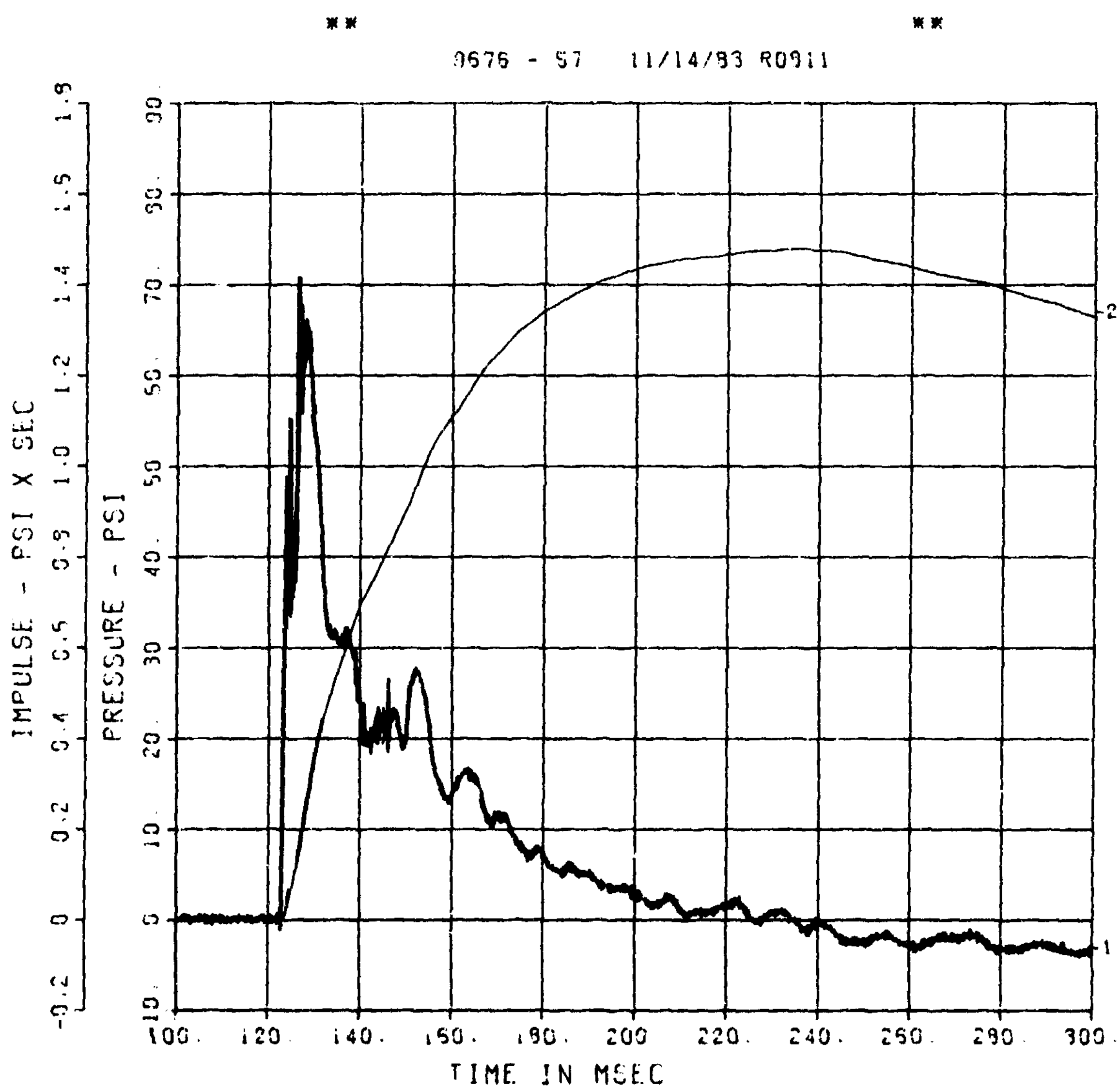


DC ENTRYWAY

P14/4095

200000. HZ CAL= 87.60

LP3/0 70% CUTOFF= 11000. HZ



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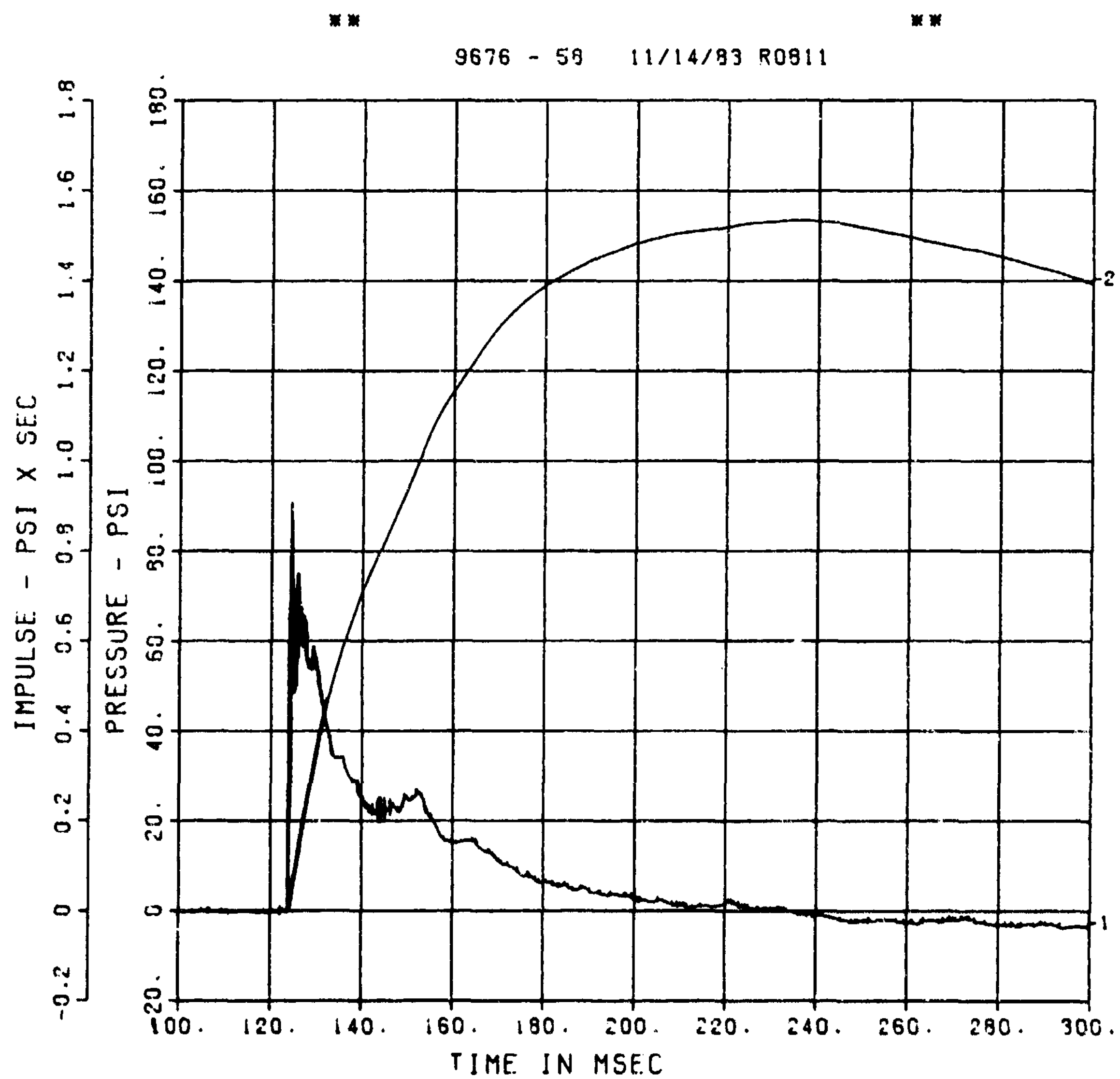

** PEAK VALUE IS 3 % OVER CALIBRATION **

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Objectives of this project were to design and test a walk-in, reinforced concrete blast shelter entryway and blast door. Two door configurations were tested: a commercially available standard exterior door with special supports, and a 3-inch-thick reinforced concrete door. The entryway and closures were tested at the DIRECT COURSE event at White Sands Missile Range, N. Mex. The DIRECT COURSE event was a 1-KT simulated nuclear airblast and ground motion environment provided by detonation of 609 tons of an ammonium nitrate-fuel oil (ANFO) mixture at a height of burst of 166 feet. The peak recorded pressure at the opening to the entryway was 69 psi and peak reflected pressure at the center of the blast door was 159 psi.

The reinforced concrete door survived the airblast effects of DIRECT COURSE with only slight permanent deformation. The commercial door was totally destroyed during the test. Post-test analyses indicate that the reinforced concrete blast door will successfully withstand the airblast effects of a 1-MT nuclear detonation at the 50-psi overpressure range.

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